Trénel (27), in comparisons between the pH of soil suspensions containing potassium chloride and the lime requirement as determined by electrometric titration, published curves which suggested a dependence of pH upon lime requirement.

Jensen (14), in an investigation of the acidity of 115 Danish fields, concluded that a single pH determination is inadequate for computing the lime requirement. Contrary to practical experience, sandy soils appeared to require more lime than loamy soils for a change in reaction. Loamy soils required more lime than sandy soils for the neutralization of exchange acidity as determined by the potassium chloride method.

Carleton (7), in a comparison of pH value with the Jones lime requirement of Quebec soils, found that soils of various types exhibited no correlation, whereas soil of the same textual character gave indications of correlation.

Saint (23), in a comparison between pH, the thiocyanate color test for estimating acidity developed by Comber (8), and the lime requirement by the Hutchinson-MacLennon method, found only a rough correlation for the soils examined. It was found that when the heavy and light soils were tabulated separately the results were much more consistent, the heavier soils giving higher lime requirements at the same pH values than the lighter soils. Organic matter also appeared to increase the lime requirement. When adjoining fields on the same farm were compared, there was a definite correlation between the lime requirement and the pH.

Arrhenius (1) has presented the following table, which attempts to predict the amount of lime or hydrated lime in kilograms per hectare which is required to change the soil reaction 1 pH unit in the alkaline direction:

SOIL TEXTURE	HUMUS CONTENT		
	Poor	Average	Rich
Sandy	500	1,000	1,500–3,000
Fine sandy	500–1,000	1,000–1,500	2,000–3,000
Light clay	1,500	2,500	3,500
Average clay	2,500	3,500	4,000
Heavy clay	3,000	4,000	4,500

Humus soils with 15 per cent organic matter—4,000–8,000

METHODS OF INVESTIGATION

Since the Jones lime requirement method has been tentatively recommended by the Association of Official Agricultural Chemists (17) and our experiences with this method for a number of years have led us to believe that it gives with reasonable accuracy the amount of lime required to bring the soil nearly to the neutral point, it was selected as a basis for comparison with the pH results.

The technique used was the modification of the Jones method proposed by Dorsey (9). Calculations were made on the basis of $CaCO_3$ requirement in pounds or tons for 2,000,000 pounds of soil.

The hydrogen-ion concentration, as expressed in pH values, was measured by the quinhydrone method of Biilman (2), using the 0.01*N* HCl–0.09*N* KCl quinhydrone half-cell of Veibel (29). A 1:1 soil-water ratio was used in the soil suspension. Results were checked by the colorimetric method, using the Morgan (18) soil testing set.

Moisture equivalents for certain of the soils studied were determined by the Briggs-McLane (5) centrifugal method, using a force equal to 1,000 times the force of gravity for 40 minutes. Mechanical analyses, when determined, were by the modified Robinson method of Engle and Youdel (10).

Organic matter determinations were made by the simplified method proposed by Schollenberger (25).

DATA AND DISCUSSION OF RESULTS

Soil reaction studies of tobacco fields

In connection with an investigation of the reaction of the tobacco soils of the Connecticut Valley, more fully presented elsewhere (19), 550 soils of textural classes ranging from coarse sand to silt loam and with organic contents ranging from 1.5 to 7 per cent were compared as to pH, lime requirement, texture, and organic content. A trained soil survey worker, by examining the color of the dry soils, estimated the organic content of all but 40 of these soils, as low, medium, high, or very high. The other 40 soils were analyzed for organic matter in the laboratory and their colors used as standards for estimating the organic contents of the previous group. The following classification of organic contents was used:

Low	Less than 2 per cent
Medium	2 to 4 per cent
High	4 to 6 per cent
Very high	6 to 8 per cent

The textures of all soils were estimated by examination and grouped into the following classes:

Sand
Loamy sand
Sandy loam
Fine sandy loam
Very fine sandy loam
Loam
Silt loam

Without consideration of the character of the soils as to organic content and texture, there appeared to be a very poor correlation between the pH and the lime requirement. This is shown in table 1, which gives data for 25 soils selected at random and arranged in the order of their pH values.

The soils were then grouped according to texture and organic content, and

the results graphically plotted. Figure 1 shows such a graph for the fine sandy loam group, for all samples with an estimate of medium (2 to 4 per cent) organic content.

It is evident at once that a good correlation exists between the lime requirement and the pH, with soils of similar texture and organic content. A similar relationship exists for all textural classes.

Two groups of soils with more than 100 individuals in each—the fine sandy

TABLE 1

Comparison of Jones lime requirements and pH values

SOIL NUMBER	pH	$CaCO_3$ REQUIREMENT FOR 2,000,000 POUNDS SOIL
		pounds
660	6.16	1,290
470	6.07	2,258
530	5.93	1,774
650	5.86	2,258
600	5.85	1,935
560	5.83	2,580
520	5.70	4,193
370	5.59	3,708
590	5.57	2,903
620	5.55	2,903
540	5.50	3,386
630	5.48	3,870
550	5.39	2,580
390	5.38	4,515
430	5.28	2,580
670	5.22	5,483
510	5.10	1,935
440	5.04	4,031
480	5.03	3,581
490	5.03	2,903
420	4.95	3,870
380	4.92	7,095
570	4.89	3,548
640	4.86	5,966
500	4.52	3,870

loam and sandy loam classes with medium organic content—were selected for calculation of correlation coefficient. The results were as follows:

Soil Groups	*Correlation Coefficient*
Fine sandy loam, medium organic content	0.757 ± 0.015
Sandy loam, medium organic content	0.856 ± 0.026

Although a perfect correlation (1.00) is far from being attained, yet since the texture and organic content were merely estimated, the results agree surprisingly.

It appeared from the graphs that the slope of the lines indicating the average relationship between pH and lime requirement became steeper with each successively heavier textural class, and that the high content of one textural class approximated the medium organic content of the next heavier texture, while soils of low organic content gave results more nearly like those of medium organic content of the next lighter class.

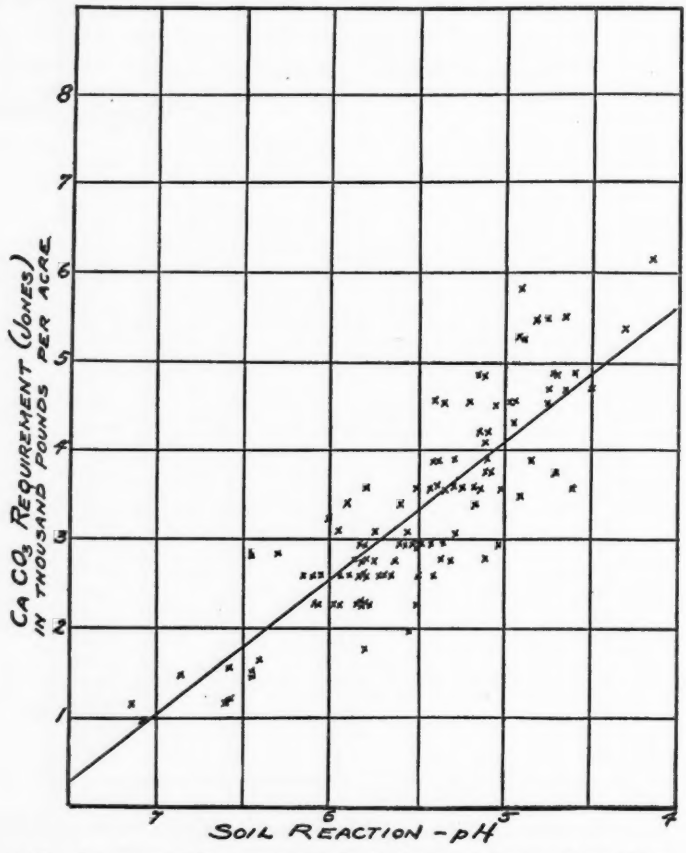

FIG. 1. THE RELATIONSHIP BETWEEN JONES $CaCO_3$ REQUIREMENT AND pH FOR 124 TOBACCO FIELDS—FINE SANDY LOAM SOIL OF MEDIUM ORGANIC CONTENT
Line indicates mathematically determined regression line

Mathematically calculated regression lines for points on the graphs should express the determined relationship between pH and lime requirement. There were sufficient points for the calculation of the equation of these lines for the soils of medium organic content of all textural classes except the silt loam.

The following values are given for the equation

$$Y = A - K(7 - x)$$

where Y = $CaCO_3$ requirement at X pH in pounds for 2,000,000,
A = $CaCO_3$ requirement at 7 pH in pounds for 2,000,000,
X = Experimentally determined pH value,
b = A constant for the soil class.

Soil Class	*Value A*	*Constant b*
Sand	225	1,100
Loamy sand	925	1,000
Sandy loam	900	1,390
Fine sandy loam	1,100	1,500
Very fine sandy loam	25	2,225
Loam	400	2,325

It is apparent from the foregoing that soils at 7 pH give a positive lime requirement, as indicated by the Jones method. This is in accord with the results of Carleton (7) and Dorsey (9). It is also observed that the slope of the curve increases with increasing fineness of texture (heaviness), with the exception of the first class, which had a relatively small number of individuals with a neutral point, which would tend to steepen abnormally the slope of the regression line.

As a result of these studies, an attempt was made to assign arbitrary values for soils of varying texture and organic content which would most simply express the aforementioned relationship between pH and organic matter. These values represent the number of pounds of $CaCO_3$ for 2,000,000 pounds of soil required to change the reaction 1 pH unit in the alkaline direction. These are shown in table 2.

Detailed Investigations

Groups of soils upon which greenhouse investigations were being conducted were subjected to more detailed study.

Fourteen soils, representing typical soil types of the state, and which were later used in lime and fertilizer trials under greenhouse conditions, were the first group to be considered.

The pH and Jones lime requirements of these soils were determined. Then 500-gm. portions of the soils were mixed thoroughly with precipitated chalk in quantities equivalent to $\frac{1}{2}$, 1, $1\frac{1}{2}$, and 2 times the Jones lime requirement, made up to optimum moisture content, and let stand for 6 weeks. At the end of this time, pH values were determined for all soils. The following data were recorded and computed, as shown in table 3:

(A) $CaCO_3$ applied, in tons to 2,000,000 pounds of soil.
(B) Increase in pH value 6 weeks after treatment.
(C) "$CaCO_3$ absorption factors" (A/B) for $\frac{1}{2}$, 1, $1\frac{1}{2}$, and 2 times Jones $CaCO_3$ requirement.

(D) Factors representing relationship between average amounts of $CaCO_3$ equivalent to ½, 1, 1½, and 2 times Jones $CaCO_3$ requirement and average values of A/B for all the soils at corresponding applications.

(E) Ratio of C to D (C/D) for ½, 1, 1½, and 2 times Jones $CaCO_3$ requirement.

(F) Average value of ratio (E) for each soil for the varying $CaCO_3$ applications, in terms of the average of the 14 soils.

TABLE 2

Factors for estimating lime requirement from pH (preliminary data—tobacco soil studies)

TEXTURE	ORGANIC MATTER	$CaCO_3$ FOR 2,000,000 POUNDS SOIL TO RAISE pH VALUE ONE UNIT
		pounds
Sand	low	1,000
	medium	1,250
	high	1,500
Loamy sand	low	1,250
	medium	1,500
	high	1,750
Sandy loam	low	1,500
	medium	1,750
	high	2,000
Fine sandy loam	low	1,750
	medium	2,000
	high	2,250
Very fine sandy loam	low	2,000
	medium	2,250
	high	2,500
Loam	low	2,250
	medium	2,500
	high	2,750
Silt loam	low	2,500
	medium	2,750
	high	3,000

It thus appears that the proportionate changes in pH for applications equal to ½, 1, 1½, and 2 times the Jones $CaCO_3$ requirement are very nearly the same for all the soils in table 3. An application of $CaCO_3$ representing one-half the Jones $CaCO_3$ requirement is 1.28 times as effective to the ton in correcting acidity as the full application, while at rates equivalent to 1½ and 2 times the Jones $CaCO_3$ requirement, limestone is 0.90 and 0.81 as efficient for a ton as for the Jones requirement quantity.

TABLE 3

Effect of applications of $CaCO_3$ in amounts representing ½, 1, 1½, and 2 times Jones $CaCO_3$ requirement, as related to specific absorptive capacity of the soil

SOIL NUMBER	(A) $CaCO_3$ ON A	pH	(B) INCREASE IN pH	(C) (A/B)	(E) (C/D)	(F) AVER. C/D
	tons					
233	0	5.05				
	1.73	6.26	1.21	1.44	1.85	
	3.46	6.98	1.93	1.79	1.79	
	5.19	7.53	2.48	2.27	2.02	
	6.92	7.92	2.87	2.41	1.94	1.90
234	0	4.81				
	2.08	5.87	1.06	1.96	2.51	
	4.16	6.87	2.06	2.02	2.02	
	6.24	7.50	2.69	2.32	2.07	
	8.32	7.75	2.94	2.83	2.27	2.22
235	0	5.32				
	1.24	6.32	1.00	1.24	1.59	
	2.48	6.98	1.66	1.49	1.49	
	3.72	7.40	2.16	1.72	1.54	
	4.96	7.81	2.49	2.00	1.61	1.56
236	0	5.48				
	1.48	6.42	0.94	1.57	1.89	
	2.96	6.98	1.50	1.90	1.90	
	4.44	7.48	2.00	2.22	1.98	
	5.92	7.81	2.33	2.54	2.05	1.96
237	0	4.76				
	2.50	5.84	1.08	2.31	2.96	
	5.00	6.38	1.62	3.08	3.08	
	7.50	6.85	2.09	3.58	3.20	
	10.00	7.42	2.66	3.75	3.02	3.07
238	0	4.85				
	2.02	5.72	0.87	2.32	2.97	
	4.04	6.15	1.30	3.10	3.10	
	6.06	6.70	1.94	3.53	3.15	
	8.08	7.02	2.26	3.57	2.88	3.02
239	0	4.70				
	2.09	5.81	1.11	1.88	2.41	
	4.18	6.32	1.62	2.58	2.58	
	6.27	6.90	2.20	2.85	2.54	
	8.26	7.51	2.81	2.97	2.39	2.48
240	0	5.40				
	1.53	6.11	0.71	2.16	2.77	
	3.06	6.39	0.99	3.09	3.09	
	4.59	6.88	1.48	3.11	2.78	
	6.12	7.14	1.74	3.51	2.83	2.87

TABLE 3—*Concluded*

SOIL NUMBER	(A) $CaCO_3$ ON A	pH	(B) INCREASE IN pH	(C) (A/B)	(E) (C/D)	(F) AVER. C/D
	tons					
241	0	4.99				
	1.50	5.94	0.95	1.58	2.03	
	3.00	6.46	1.47	2.04	2.04	
	4.50	7.15	2.16	2.08	1.86	
	6.00	7.45	2.46	2.43	1.96	1.97
242	0	5.14				
	1.37	6.04	0.90	1.52	1.95	
	2.74	6.58	1.44	1.90	1.90	
	4.11	7.16	2.02	2.03	1.81	
	5.48	7.54	2.40	2.28	1.84	1.88
243	0	4.59				
	1.64	5.91	1.32	1.24	1.59	
	3.28	8.81	2.29	1.43	1.43	
	4.92	7.53	2.94	1.67	1.49	
	6.56	7.90	3.31	1.98	1.60	1.53
244	0	4.18				
	1.53	5.76	1.58	0.96	1.23	
	3.06	6.69	2.51	1.21	1.21	
	4.59	7.33	3.15	1.45	1.29	
	6.12	7.73	3.55	1.72	1.39	1.28
245	0	4.93				
	1.50	5.92	0.99	1.51	1.94	
	3.01	6.27	1.34	2.24	2.24	
	4.51	7.16	2.23	2.02	1.80	
	6.02	7.62	2.69	2.23	1.80	1.94
246	0	4.80				
	1.55	6.14	1.34	1.15	1.47	
	3.10	6.91	2.11	1.42	1.42	
	4.65	7.10	2.30	2.02	1.80	
	6.20	7.51	2.71	2.28	1.84	1.63

Average value A/B for all soils: (D)

½ Jones $CaCO_3$ Req.—1.63 = 0.78
Jones $CaCO_3$ Req.—2.09 = 1.00
1½ Jones $CaCO_3$ Req.—2.34 = 1.12
2 Jones $CaCO_3$ Req.—2.60 = 1.24

} x A/B for amount of $CaCO_3$ representing Jones $CaCO_3$ requirement.

It is also seen from table 3 that in no case has an application of calcium carbonate, thoroughly incorporated with the soil, and equivalent to the Jones $CaCO_3$ requirement, been sufficient to produce a reaction of 7.0 pH, but in all cases it has decreased the acidity to above 6.15 pH and to an average for the 14 soils of 6.63 pH.

There is a practically constant relationship among the different soils as to the amount of $CaCO_3$ required to produce an increase of 1 pH in the soil reaction, whether computed from $\frac{1}{2}$, 1, $1\frac{1}{2}$, or 2 times the Jones $CaCO_3$ requirement rates of application. This apparently indicates that the ratio of the Jones $CaCO_3$ requirement to the difference between the determined pH and 7 pH is a measure of a specific property or summation of properties characteristic of the particular soil in question. The general agreement of value *E* in table 3 for varying amounts of $CaCO_3$ applied to the same soil suggests strikingly that the order of magnitude of the average of these values, expressed as value *F* is a measure of the specific absorptive capacity of the soil. Thus for soil 237, the value *F* is 3.07, whereas for soil 244 it is only 1.28. It is of interest to note some of the characteristics of these two soils:

	Soil 237 per cent	*Soil 244 per cent*
Organic content	8.34	2.79
Colloid content (Bouyoucos Hydrometer method)	14.89	12.20
Mechanical analysis		
Fine gravel	2.77	1.00
Coarse sand	5.30	5.62
Medium sand	9.20	14.57
Fine sand	27.45	28.73
Very fine sand	22.90	19.40
Total sands	67.62	69.32
Silt	16.45	14.98
Clay	19.70	15.70
Moisture equivalent	15.27	9.49
Hygroscopic coefficient	2.26	1.09

In an effort to ascertain the factors which cause differences in the amount of lime required to effect a given change in reaction for various soils, a series of 56 soils of varying types and ranging in reaction between 4.18 and 6.21 pH, were investigated as to texture (determined from mechanical analyses), organic content, moisture equivalent, hygroscopic coefficient, pH, and $CaCO_3$ requirements as determined by both the Jones and the Hardy (12) electrometric titration methods. The results are given in table 4.

There was a good agreement between the two lime requirement methods on most of the soils. To reduce the possible error due to the individualities of the method of measurement, lime requirements by the two methods were averaged for the purpose of further correlation.

A "$CaCO_3$ absorption factor" was computed for each soil, by dividing the average $CaCO_3$ requirement, as expressed in tons to 2,000,000 pounds of soil, by the difference between 7 pH and the determined pH.

The moisture equivalent and the hygroscopic coefficients appeared to be affected by both the texture and the organic content of the soil.

The moisture equivalent is essentially a single value numerical expression of the summation of the absorptive characteristics of the soil, as affected

TABLE 4

Factors related to lime requirement for 56 Connecticut soils

SOIL NUMBER	pH	TEXTUAL CLASS	ORGANIC CONTENT	$CaCO_3$ REQUIREMENT AN ACRE			CALCULATED $CaCO_3$ ABSORPTION FACTOR	MOISTURE EQUIVALENT
				Jones	Hardy	Average		
			per cent	*tons*	*tons*	*tons*		
1	4.74	f.s.l.	3.52	2.95	2.79	2.87	1.27	11.49
2	4.74	f.s.l.	3.24	3.10	3.11	3.09	1.37	11.95
3	6.21	loam	4.33	1.65	1.55	1.60	2.03	17.48
4	4.99	l.f.s.	4.86	2.75	2.19	2.47	1.23	10.72
5	5.07	f.s.l.	4.72	3.15	3.07	3.11	1.61	16.98
6	5.31	f.s.l.	4.38	2.65	1.91	2.23	1.32	13.91
7	5.04	f.s.l.	5.71	3.50	2.42	2.96	1.51	13.24
8	5.16	l.f.s.	5.81	3.10	2.78	2.94	1.60	12.73
9	4.85	loam	11.31	4.90	4.00	4.45	2.07	18.34
10	5.96	l.f.s.	3.45	0.95	1.35	1.15	1.11	12.46
11	4.85	f.s.l.	3.84	2.94	2.86	2.90	1.35	14.25
12	4.96	f.s.l.	5.70	3.40	2.84	3.12	1.53	13.37
19	4.94	sand	0.85	1.10	1.32	1.21	0.53	4.72
21	5.52	l.s.	1.32	1.35	1.13	1.24	0.84	6.26
65	4.88	l.s.	1.31	1.90	1.88	1.89	0.89	8.44
73	4.60	l.s.	2.43	2.40	2.40	2.40	1.00	7.62
87	4.44	sand	0.41	0.70	0.78	0.74	0.29	3.04
223	5.42	l.s.	2.41	1.37	1.31	1.34	0.85	3.78
224	5.26	l.s.	1.99	1.77	1.53	1.65	0.95	5.22
225	5.11	f.s.l.	4.10	2.59	2.59	2.59	1.37	13.72
226	5.96	f.s.l.	3.74	1.19	1.17	1.18	1.14	10.48
227	5.76	loam	3.74	2.24	1.95	2.10	1.69	14.24
228	5.06	f.s.l.	3.81	2.54	3.03	2.79	1.44	10.34
229	5.17	f.s.l.	4.58	3.07	3.29	3.18	1.74	13.23
230	5.10	f.s.l.	3.50	2.91	2.70	2.79	1.47	10.77
231	4.77	f.s.l.	5.29	3.79	4.10	3.84	1.72	16.66
233	5.05	f.s.l.	6.02	3.10	3.26	3.18	1.63	11.95
234	4.81	loam	6.60	4.16	3.94	4.05	1.85	18.31
235	5.32	loam	2.98	2.48	2.02	2.25	1.34	13.72
236	5.48	f.s.l.	3.86	2.76	2.27	2.53	1.71	10.50
237	4.76	f.s.l.	8.34	5.00	3.90	4.43	1.98	15.27
238	4.85	f.s.l.	5.31	4.04	3.14	3.59	1.67	10.03
239	4.70	f.s.l.	6.41	4.18	3.15	3.79	1.69	10.40
240	5.40	f.s.l.	6.83	3.06	3.12	3.09	1.92	15.95
241	4.99	f.s.l.	5.00	3.00	3.00	3.00	1.49	12.12
242	5.14	s.l.	3.98	2.74	2.94	2.84	1.52	10.04
243	4.59	f.s.l.	3.16	3.28	2.41	2.84	1.18	11.26
244	4.18	s.l.	2.79	3.06	2.98	3.02	1.07	9.49
245	4.93	si.l.	3.93	3.01	2.99	3.00	1.45	18.15
246	4.80	v.f.s.l.	3.53	3.10	2.70	2.90	1.32	10.97
310	5.04	loam	4.72	3.25	3.30	3.27	1.67	15.79
311	5.36	loam	4.20	2.61	2.40	2.49	1.52	14.83
312	4.79	loam	3.88	3.20	2.33	2.74	1.24	10.60
313	4.92	loam	4.44	3.42	2.85	3.12	1.50	15.23
314	5.17	loam	6.08	3.42	3.12	3.27	1.79	18.30

TABLE 4—*Concluded*

SOIL NUMBER	pH	TEXTUAL CLASS	ORGANIC CONTENT	$CaCO_3$ REQUIREMENT AN ACRE			CALCULATED $CaCO_3$ ABSORPTION FACTOR	MOISTURE EQUIVALENT
				Jones	Hardy	Average		
			per cent	*tons*	*tons*	*tons*		
315	5.27	loam	11.44	4.86	4.20	4.53	2.62	22.33
316	5.23	loam	7.06	3.22	2.85	3.04	1.72	16.69
317	5.18	f.s.l.	3.86	2.43	1.95	2.18	1.20	9.50
318	4.72	loam	9.35	5.94	4.95	5.06	2.22	18.86
319	4.91	f.s.l.	6.64	4.45	3.15	3.80	1.82	13.79
320	5.36	f.s.l.	5.80	2.63	2.18	2.40	1.46	12.00
321	4.73	loam	11.56	4.76	6.58	5.67	2.50	20.30
322	5.24	l.f.s.	2.78	2.05	2.25	2.15	1.22	9.13
323	5.26	f.s.l.	5.36	2.54	1.95	2.25	1.37	15.99
324	4.93	loam	5.84	4.10	3.15	3.64	1.75	16.48
326	5.02	sand	1.06	1.50	1.36	1.43	0.72	5.29

chiefly by texture and organic content. It must be kept in mind that the actual H-ion concentration is decreased by ten times with each unit increase in pH value. A straight line correlation between the amount of lime required to produce a unit increase in pH value and these absorptive characteristics of the soil implies a logarithmic correlation between the lime required to produce a unit change in pH value and the moisture equivalent or similar expression of absorptive soil properties. Here again we seem to be dealing with the phenomenon which has been pointed out by Prescott (21), Fisher (11), Salter and Morgan (24), and many other workers: the acidity and lime requirement of the soil is controlled by the well-known absorption isotherm of Freundlich ($X/M = C^{1/n}$).

Data for the hygroscopic coefficient are omitted from table 4, since the moisture equivalent and hygroscopic coefficient were in close relationship. This is in agreement with the results of Russell and Burr (21).

The results of comparisons between the $CaCO_3$ absorption factors and moisture equivalents are represented graphically in figure 2. It is apparent that there is a straight line correlation between these $CaCO_3$ absorption factors and moisture equivalents. This can be approximately expressed by the equation

$$CaCO_3 \text{ absorption factor} = 0.119 \times \text{Moisture Equivalent}$$

Estimation of lime requirement from pH values

On the basis of the foregoing results, a table of "$CaCO_3$ absorption factors" for soil of various types was prepared. This can be done by calculation to the nearest 0.25 from the average moisture equivalent values at different textures and organic contents. From these $CaCO_3$ absorption factors the lime requirements, as expressed in terms of amounts of $CaCO_3$ in tons to 2,000,000 pounds required to produce a neutral reaction, can be calculated as the product of the $CaCO_3$ absorption factor and the difference between the pH of the soil and 7 pH.

$$CaCO_3 \text{ requirement in tons to 2,000,000 pounds} = CaCO_3 \text{ absorption factor} \times (7 - \times \text{pH}).$$

In case it is desired to bring a soil to a pH of 6.0, rather than 7, the data presented in this paper indicate that the factors can be diminished to approximately four-fifths the above values, and the calculation becomes:

$$\text{CaCO}_3 \text{ requirement in tons for 2,000,000 pounds to produce reaction of 6 pH} = 0.8 \text{ CaCO}_3 \text{ absorption Factor} \times (6 - \text{x pH})$$

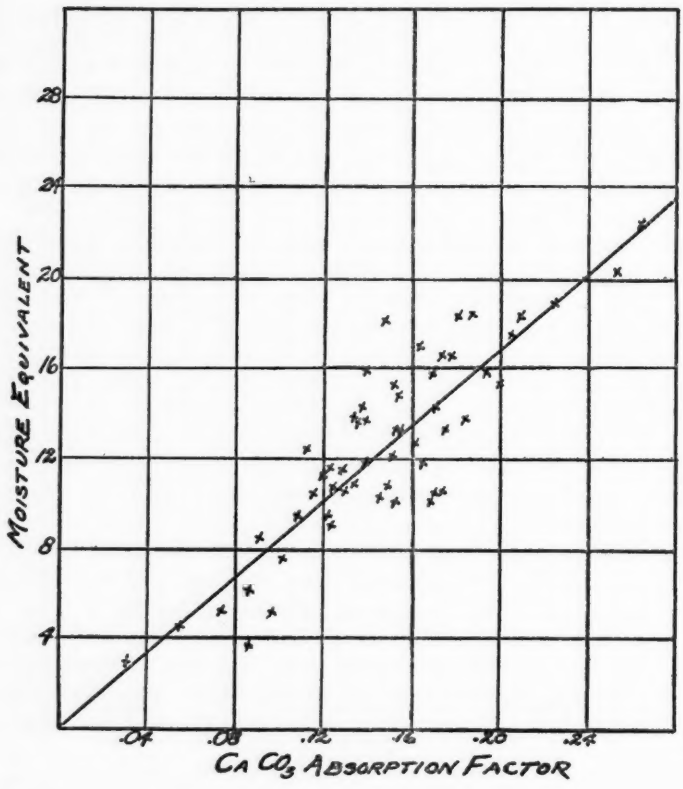

FIG. 2. RELATIONSHIP BETWEEN MOISTURE EQUIVALENTS AND "$CaCO_3$ ABSORPTION FACTORS" FOR FIFTY-SIX CONNECTICUT SOILS

The $CaCO_3$ absorption factor is the calculated amount of $CaCO_3$ in tons to 2,000,000 pounds of soil required to produce a change of 1 pH toward 7 pH.

Thus, a soil of silt loam texture and 4 per cent organic content, testing 4.6 pH, which one wishes to correct to 6 pH, will require $0.8 \times 2.00 \times (6 - 4.6) = 2.24$ tons $CaCO_3$ an acre.

It is not believed that anything like perfect accuracy can be attained by this

method of prediction. Other factors, such as the presence of unusual concentrations of buffer compounds like superphosphates and calcium or magnesium salts may also affect the relationship between lime requirement and pH. However, an accuracy which is correct to within a half ton quantity of limestone an acre is sufficient as a basis of practical recommendation. A series of 100 soils of varying types from Connecticut, and not included in the foregoing data, were examined in order to test the practical validity of this scheme for estimating limestone ($CaCO_3$) requirement from pH values. Eighty-nine of these soils gave calculated results which checked with the Jones $CaCO_3$ requirement within a half ton an acre, and the widest discrepancy was -1.24 tons on a soil with a Jones $CaCO_3$ requirement of 5.61 tons.

It is also to be observed that the factors for the estimation of $CaCO_3$ requirement from pH values as given in the foregoing are slightly different than those presented in connection with the study of the reaction and lime requirement of tobacco soils. The difference is largely due to the fact that the latter were obtained from estimated texture and organic content on a group of soils which are in general more sandy in character than most of the soils which were investigated in more detail. It is believed that the factors presented in table 5 are somewhat more accurate and suitable for a wider application than those given in table 2.

TABLE 5

Proposed $CaCO_3$ absorption factors as estimated from textural class and organic content

SOIL CLASS	$CaCO_3$ ABSORPTION FACTORS			
	0–2.5% O.M.*	2.5–5% O.M.	5–7.5% O.M.	7.5–10% O.M.
Sand	0.25	0.50	0.75	1.00
Loamy sand	0.50	0.75	1.00	1.25
Sandy loam	0.75	1.00	1.25	1.50
Fine sandy loam	1.00	1.25	1.50	1.75
Loam	1.25	1.50	1.75	2.00
Silt loam	1.50	1.75	2.00	2.25
Clay loam	1.75	2.00	2.25	2.50
Clay	2.00	2.25	2.50	2.75
	Percentage of organic matter			
	10–20	20–40	40–60	Over 60
Organic soils	2.5–5.0	5.0–7.0	7.0–9.0	9.0–12.0

* O.M. = organic matter.

SUMMARY

The increasing use of pH tests in soil studies presents a growing need for the practical utilization of these tests as a guide to liming practice.

Results of previous investigation have, in general, indicated a correlation

between pH and lime requirement, particularly on soils of the same type. The factors which affect this correlation have not been studied in detail.

In a study of the reaction and lime requirements of several hundred tobacco fields in the Connecticut Valley, a tabulation of the data showed an excellent correlation between pH and lime requirement for soils of approximately the same texture and organic content. An increase in organic matter and a heavier texture both produce a larger value of the "lime absorption factor," which represented the amount of lime required to decrease the acidity 1 pH. An approximate table of factors was calculated which appeared to be of general application to this group of soils.

More detailed studies were conducted on other soils which have been under investigation in the greenhouses of the Connecticut Agricultural Experiment Station, and which represent all the important soil types of the state. A study of the rate of change in reaction produced by amounts of $CaCO_3$ corresponding to $\frac{1}{2}$, 1, $1\frac{1}{2}$, and 2 times the Jones lime requirement on 14 of these soils revealed the fact that there is a constant difference in relative effectiveness of lime in these proportions, and that a constant factor is in operation on each individual soil which determines the amount of lime required to produce a given change in pH toward the neutral point. An inspection of these data as related to the physical characteristics of these soils, suggests that the value of this factor can be approximately determined from a study of the mechanical analysis, organic content, and moisture constants of the soil.

A group of 56 soils were thus investigated. A most striking correlation between moisture equivalent and the "$CaCO_3$ absorption factor" was revealed. Since the moisture equivalent is in effect a measure of the summation of the effect of differences in texture and organic content upon the absorptive properties of the soil, this result is not difficult to explain. It lends weight to the view that the lime requirement of the soil is a logarithmic function of the actual H-ion concentration and a direct function of the specific absorptive characteristics of the soil.

Since the amount of $CaCO_3$ required to produce a change of 1 pH in reaction toward 7 pH can be expressed by multiplying the moisture equivalent by the factor 0.119, and since the moisture equivalents of soils of different textures and organic contents are relatively constant, a table of $CaCO_3$ absorption factors for the various textural classes at varying organic contents has been prepared. It has proved to be of good general application on a group of 100 random samples of soils from all parts of Connecticut, and is believed by the writer to be suitable for the estimation of lime requirement from pH values for most normal soils in the humid region of eastern United States.

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PERIODICITY OF THE NITRATE CONTENT OF SOILS

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Nitrate is the most important plant-food in the soil and has been studied from different points of view in different countries of the world. Much information regarding the process has been accumulated and it has come to be generally recognized that there are certain conditions in the soil which to a large extent control the production of nitrates or regulate the activity of the organisms concerned with the final production of nitrate.

Some investigators have also studied the fluctuations which the nitrate content of the soil undergoes during the different periods, in other words, the seasonal variations of the amount of nitric nitrogen or of the bacterial activity in the soil. Some of them carried out experiments under field conditions, and others under laboratory conditions. It has been recognized that there are definite seasonal changes in the nitrate content of soils, but opinions differ as regards the period when the greatest accumulation of nitrate occurs in the soil. Some have inferred from their experimental data that it takes place during summer months, others during spring or autumn months; but winter has been accepted by all as the period when least accumulation takes place.

It is proposed, therefore, to give in this paper the data obtained in different parts of the world relating to the seasonal variations of the amount of nitrates in soils, to review the whole of the results, to ascertain the periods when the nitrifying activity is most intense, and to trace the exact relation between the fluctuations of the nitric nitrogen of soils and the different seasons of the year.

Pouget and Guirraud (14) in France, Montanari (12) in Italy, Jensen (8) in South Dakota, Vogel (21) in Russia, Russell (16) in England, Green (6) and Lemmermann and Wichers (10) in Germany, Fraps (4) in Texas, Whiting and Schoonover (23) in Illinois, Prescott (15) in Egypt, Hall (7) in South Africa, Gowda (5) in Iowa, Leather (9) and Clarke (2) in India, and Taylor (20) in New South Wales studied the accumulations of nitric nitrogen in soils during the different parts of the year. The averages of their results are given in table 1, except those of Montanari and Vogel, for the journals containing their original papers were not available. According to abstracts in the Experiment

[1] The authors wish to express their thanks to Mr. G. Clarke, director of agriculture, United Provinces, India, for his valuable suggestions and help.

Station Record, however, Montanari concludes that, "the quantity of nitric nitrogen in soils variously cultivated is least in February, March, and June, and most in July and August"; and Vogel concludes that "the rate of nitrification varied widely with the time of the year, being highest in October and November, then falling steadily until April, when it rose again but not so high as in the autumn." The authors also have studied the accumulation of nitrates in the soil under laboratory conditions with optimum moisture content, and their average results are also included in table 1. The details of the experimental method have already been published (1). Figures of soils bearing crops generally have not been included in the table, because crops can interfere with the seasonal changes of nitrate in soils. Most of the figures given in part A of table 1 belong to the Northern Hemisphere, and those in part B to the Southern Hemisphere.

From the investigations made upon the production of nitrates in field soils, three factors appear to exert an influence upon it. The first factor is soil treatment, such as application of organic matter, limestone, phosphorous, and potassium; the second is the tillage operations, such as plowing, cultivation, fallowing, mulching; and the third, climatic conditions, such as temperature and moisture.

There seems to be no doubt that nitrification is affected very materially by changes in these factors, still it has been shown by different workers that the decrease or increase in the amounts of nitrates can not be wholly explained by these factors. For instance, Hall, while discussing the influence of temperature and moisture upon the nitric nitrogen content of the South African soil, says "In fact, the nitrate curves on the whole fit the rainfall diagram better than they do the one for temperature." Russell and Appleyard (17) have stated that "the three factors, temperature, moisture, and [the third, which they believed to be] the supply of dissolved oxygen, fit the nitrate and CO_2 curves tolerably well over a large part of the year and thus suffice to account for most of the phenomena, but there still remain two periods which are not fitted and where, therefore, some other factors must be operating; a period of depression coming after the spring rise and a period of autumn activity after the summer sluggishness." We must see, therefore, what further factors may be involved. Thus the factors studied so far do not fully explain the fluctuations which the nitric nitrogen content of the soil undergoes all the year round. Fraps when studying the nitrate content of plots under different crops says, "The nature of the season apparently has a marked effect on the results obtained." Jensen also says that even when all these factors are considered there would appear to be a rhythmic periodicity of nitrifying activity during the season due to some unknown property of the bacteria.

It is a well-known fact that higher forms of life—plants and animals—are more active at certain periods of the year than at others; it is quite possible that lower forms of organisms, such as nitrifying bacteria, may be following the same rule. As Vogel says, "The treatment of the soil had less effect upon

nitrification than the time of the year"; so let us see how far the activity of the nitrifying bacteria is influenced by different times or seasons of the year.

From table 1 or from table 2, where the figures of table 1 are expressed in relation to the lowest analytical number stated as 100, it can be seen, by taking each country individually, that the amounts of nitric nitrogen obtained for each month are not the same but differ widely from one another, indicating thereby that the activity of the bacteria varies every month.

Of all the places mentioned in the table, only two (South Africa and New South Wales) lie in the Southern Hemisphere. The solar activity in the Northern Hemisphere is greatest on June 22, after which it decreases daily till December 22 when it again begins gradually to increase. Thus the effect of the solar activity on the surface of the earth in the Northern Hemisphere is greatest in the months of June and July and least in the months of December and January. The figures of different places in the Northern Hemisphere, as given in table 2, part A, show that in most cases the nitric nitrogen content of the soils is at its maximum in June or July and at its minimum in December or January.

It is also observable, particularly from the figures of such places as Germany, Texas, and Cawnpore (India), where the determinations were carried out for nearly the whole year, that the trend of the nitrate content of soils is downward from summer to winter and upward from winter to summer; though this fall or rise is not so regular and continuous as that in the intensity of insolation during the above months, because of some other factors that come into play.

The tendency of the variations in the nitrate content of soils to correspond with the changes in the strength of the sun's rays, becomes more evident when the amounts of nitric nitrogen found in different months of the year are arranged according to seasons, as in table 3, in which are included only those countries where determinations were carried out for at least 9 months in the year. The maximum solar activity occurs during summer, and the minimum during winter; accordingly the mean of the average figures of each season of the Northern Hemisphere, as given in table 3, shows that the greatest quantity of nitrates is found during the summer and the least during the winter. Further when the mean of the average figures of the autumn and spring seasons of the Northern Hemisphere are considered, they are nearly the same, and both of them are greater than the winter figures and less than the summer ones; because since the two seasons are equinoctial, the earth receives nearly the same measure of solar activity, which is greater than that received during the winter and less than that received during the summer.

The Northern and Southern Hemispheres are reciprocal in their seasons and in the lengths of their days and nights. In the Southern Hemisphere the days are longest during December and January. Accordingly the strength of the sun's rays is at its maximum in these months and the nitrate content of the soils of the Southern Hemisphere must also be greatest at this time of the year.

The figures of the two countries of the Southern Hemisphere, as given in

TABLE 1

Nitrate accumulation in the soil during different months as determined by various investigators

COUNTRY	YEAR	NAME OF WORKER	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER	
Part A															
France	1907	Pouget and Guirraud	4.8	2.0	.....	trace	2.6	6.0	4.6	.....	.....	.....	.....	1.0	mgm. per kgm.
South Dakota (U. S.)	1909–10	Jensen	.....	.....	.....	15	31	55	47	.....	.....	.....	.....	.....	p.p.m.
Pusa (India)	1910	Leather	.....	.....	.....	3.1	3.5	21.6	28.4	3.6	4.3	6.4	.....	.....	lbs. per acre
England	1912	Russell	.....	24.0	21.5	27.0	22.5	39.0	45.0	.....	19.0	.....	.....	.....	lbs. per acre
Oberholz (Germany)	1912–13	Green	.....	111	123	132	134	.....	125	114	121	107	103	102	
Texas (U. S.)	1913–16	Fraps	1.4	2.4	1.7	1.7	6.6	8.7	8.3	6.2	4.5	6.8	1.7	1.7	p.p.m.
Illinois (U. S.)	1916	Whiting and Schoonover	.....	.....	.....	33.3	34.8	48.5	38.5	43.9	46.7	65.2	47.2	38.5	lbs. per acre.
Egypt	1917	Prescott	19.2	23.0	28.2	.....	.....	.....	.....	.....	.....	.....	9.0	12.9	p.p.m.
Cawnpore (India)	1919–20	Clarke	10.3	.....	16.3	13.6	.....	.....	.....	.....	3.1	9.6	9.8	.....	p.p.m.
Germany	1920	Lemmermann and Wichers	5.4	5.2	5.5	10.3	10.5	7.1	13.7	6.9	.....	6.7	6.1	5.0	mgm. of nitrates from 21.2 mgm. NH_3 in 5 gm. of soil.
Iowa (U. S.)	1923	Gowda	.....	.....	.....	.....	.....	61.28	44.02	16.93	11.30	17.42	.....	.....	lbs. per acre.
Cawnpore (India)	1923–24	Batham and Nigam	3.61	4.03	3.83	4.47	5.35	6.29	6.89	3.71	3.61	.....	4.13	.....	pts. per 100.
Part B															
South Africa	1919–20	Hall	33.5	13.6	7.3	9.5	9.0	22.5	24.6	16.2	.....	28.2	25.6	49.0	p.p.m.
New South Wales	1921–22	Taylor	9.4	7.7	8.5	.....	.....	3.0	5.2	2.0	3.1	3.6	5.4	3.4	p.p.m.

TABLE 2

Relative nitrate accumulation in the soil during different months, the lowest analytical number given by each investigator (table 1) being taken as 100

COUNTRY	YEAR	NAME OF WORKER	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
Part A														
France	1907	Pouget and Guiraud	480	200	.....	traces	260	600	460	.....	.....	.....	.....	100
United States	1909–10	Jensen	.....	.....	.....	100	207	367	313	.....	.....	.....	.....	.....
Pusa (India)	1910	Leather	.....	.....	.....	100	113	697	916	116	139	206	.....	.....
England	1912	Russell	.....	126	113	142	118	205	237	.....	100	.....	.....	.....
Oberholz (Germany)	1912–13	Green	.....	111	123	132	134	.....	125	114	121	107	103	102
Texas	1913–16	Fraps	100	171	121	121	471	621	593	443	321	486	121	121
Illinois	1915	Whiting and Schoonover	.....	.....	.....	100	104	146	116	132	140	196	142	116
Egypt	1917	Prescott	213	255	313	.....	.....	.....	.....	.....	.....	.....	100	143
Cawnpore (India)	1919–20	Clarke	332	.....	526	439	.....	.....	.....	.....	100	310	316	.....
Germany	1920	Lemmermann and Wichers	108	104	110	206	210	142	274	138	.....	134	122	100
Iowa	1923	Gowda	.....	.....	.....	.....	.....	542	389	150	100	154	.....	.....
Cawnpore (India)	1923–24	Batham and Nigam	100	112	106	124	148	174	191	103	100	.....	114	.....
Part B														
South Africa	1919–20	Hall	459	186	100	130	123	308	337	222	.....	386	351	671
New South Wales	1921–22	Taylor	470	385	425	.....	.....	150	260	100	155	180	270	170

tables 1 and 2, show that the greatest amount of nitrates is found in December or January. But in neither place is the least found during June and July, when the strength of the sun is at its minimum. With regard to a rise in June in the South African soil, Hall says, "During the last week in May there were killing frosts. This may perhaps be explained by the biological theory of partial sterilization, of Russell and Hutchinson, which they apply to heated soils. The frost, like the heat, may kill the protozoa and other enemies of nitrifying bacteria, which then become more active and an increase in nitrates is found as a result." Considering the figures of New South Wales, though the smallest quantity is not found in June or July, still there is not much difference between the quantity of June and the least quantity of August, which is also one of the winter months.

Again if the mean of the average figures of different seasons of the Southern Hemisphere, as given in table 3, is taken into account, the greatest quantity of nitrates appears to exist during summer, and the least during winter. There does not appear to be much difference between the figures of autumn and spring and at the same time they lie between the extremes, as has been shown in the case of the Northern Hemisphere.

It is therefore evident from the mean of the average figures of different seasons of the two hemispheres that the greatest accumulation of nitrates take place during the summer and the least during the winter, and that the accumulations during spring and autumn are nearly equal and are midway between those of summer and winter; thus a close relationship is indicated between the fluctuations of nitrate content of soils and the different seasons of the year.

As the two hemispheres are reciprocal in their seasons so they are reciprocal in the nitrate content of the soils during different seasons (fig. 1).

The fluctuations in the nitrate content of soils represent one of the most important biochemical changes occurring in the soil and are believed to be brought about by the microörganic population. Attempts have been made to correlate these fluctuations with the bacterial activity.

Russell studied the problem in some detail at Rothamsted and determined the bacterial numbers, the nitrate content of the soils, and the amount of CO_2 in the soil air at frequent intervals for a period of two seasons on several plots. In his book (18) he says, "The period of summer sluggishness is followed by one of considerable activity in autumn and this in turn by the period of winter inertness. . . . . These periods of spring activity, summer sluggishness, and autumn activity seem to be fairly general and they have been recorded elsewhere."

In support of the above statement he quotes the work of several investigators: Löhnis and Sabaschnikoff (11), Munz and Gaudechon (13), Conn (3), Leather (9), Jensen (8), and others.

Löhnis and Sabaschnikoff carried out the investigations for 6 months, March, April, May, July, August, and October, missing the month of June. The curve of their findings resembles the sand curve of Russell and not the

TABLE 3

Nitrate accumulation in the soil during different months, grouped according to seasons

Part A—Northern Hemisphere

COUNTRY	YEAR	NAME OF WORKER	WINTER				SPRING				SUMMER				AUTUMN			
			December	January	February	Average	March	April	May	Average	June	July	August	Average	September	October	November	Average
Oberholz (Germany)	1912–13	Green	102	....	111	106	123	132	134	130	....	125	114	119	121	107	103	110
Texas	1913–16	Fraps	121	100	171	131	121	121	471	238	621	593	443	552	321	486	121	309
Illinois	1915	Whiting and Schoonover	116	....	....	116	....	100	104	102	146	116	132	131	140	196	142	159
Germany	1920	Lemmermann and Wicher	100	108	104	104	110	206	210	175	142	274	138	185	....	134	122	128
Cawnpore (India)	1923–24	Batham and Nigam	....	100	112	106	106	124	148	126	174	191	103	156	100	....	114	107
Mean of averages						113				154				229				163

Part B—Southern Hemisphere

COUNTRY	YEAR	NAME OF WORKER	WINTER				SPRING				SUMMER				AUTUMN			
			June	July	August	Average	September	October	November	Average	December	January	February	Average	March	April	May	Average
South Africa	1919–20	Hall	308	337	222	289	....	386	351	368	671	459	186	439	100	130	123	118
New South Wales	1921–22	Taylor	150	260	100	170	155	180	270	202	170	470	385	342	425	....	....	425
Mean of averages						229				285				390				271

loam one, which is the typical land for agriculture, which is most suitable for the accumulation of nitrates, and in which the greatest quantity of nitrate was found by him during summer.

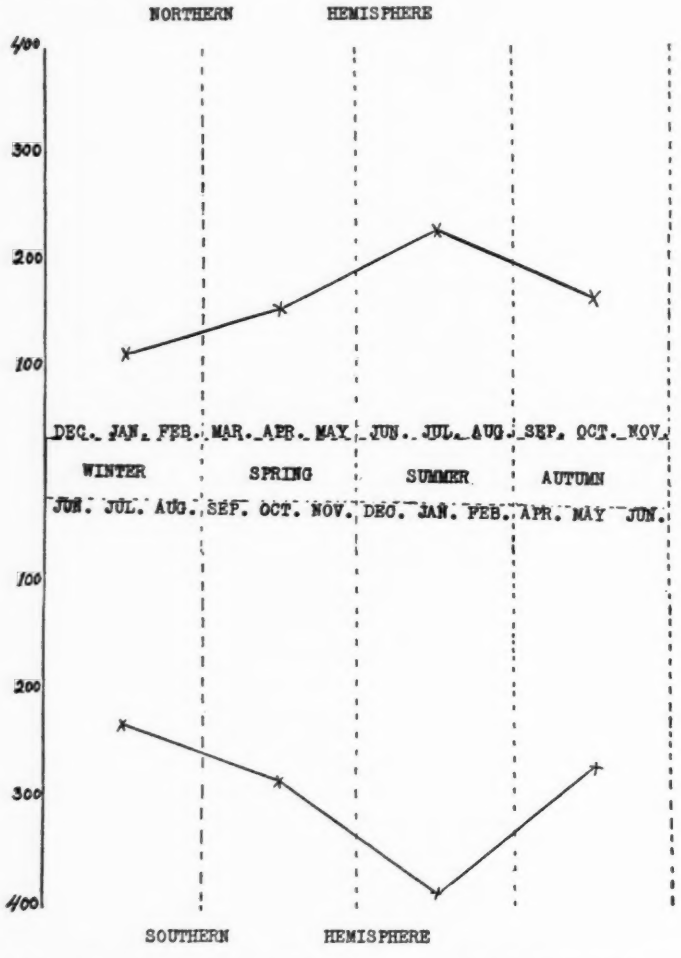

FIG. 1. RECIPROCALITY OF THE CHANGES IN NITRIC NITROGEN OF SOILS OF THE NORTHERN AND SOUTHERN HEMISPHERES ACCORDING TO THE RECIPROCALITY OF THE SEASONS

Munz and Gaudechon performed their experiments of nitrate estimations for only four months, February, March, April, and May, and therefore their results can not indicate whether the greatest accumulation of nitrates takes place in spring or summer.

Conn found the greatest number of bacteria in February.

Leather determined the nitrates for six months, from April to September, and found the greatest accumulation in June and July.

Jensen's nitrate curves reach their highest peak on June 12, after which there is a decrease, but the general level of the curves in June and July remains at a higher level than in April and May.

Quite recently, Smith (19) has shown by means of graphs that the greatest accumulation of nitrates took place in July.

Thus the majority of the results of the investigations point out that the greatest accumulation of nitric nitrogen occurs in soils during summer months.

Taylor (20) also studied the question from a chemical as well as from a bacteriological point of view and made bacterial counts during different seasons of the year. He concludes that bacterial numbers are just average and tend to rise to a more or less uniform level for the hotter months and sink to lower figures in the colder, wetter months.

With regard to bacterial numbers, Waksman (22) says, "Several investigators found larger bacterial numbers in the soil in summer than in winter, the maximum being reached in July and August."

Thus summer appears to be the best period for the conditions which assist the bacterial agencies to accumulate nitrates in the soil, and winter, the worst. A study of nitrification during the summer seasons is being carried on by the authors and may lead to a better knowledge of factors most congenial for nitrification.

Changes in the position of the sun with respect to the earth bring about changes in the activity of the sun upon the earth, giving rise to different seasons of the year. These changes in the activity of the sun produce corresponding changes in the distribution of temperature, pressure, and rainfall, in spite of other factors such as, land, sea, and altitude, which come into play and modify them. Similarly the fluctuations of the nitric nitrogen content of soils or the activity of the nitrifying bacteria may follow exactly the variations of the solar activity, except for the factors mentioned which modify its corresponding fluctuations.

Thus the solar activity appears to be a most important factor in controlling the nitrifying bacterial activity or the accumulation of nitrates in soils.

SUMMARY

The data collected regarding the seasonal variations of the nitrate content of soils from various countries of the world show:

1. That the greatest accumulation of nitrates takes place during summer months and the least during winter ones.

2. That there seems to exist a close relationship between the fluctuations of nitric nitrogen content of soils and different seasons of the year.

3. That the solar activity, which appears on the earth in the form of different seasons of the year, seems to be a most important factor in controlling the nitrifying bacterial activity in soils.

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A HOLDER FOR SOIL SAMPLE BAGS

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A simple device which has been successfully used for holding open the small canvas bags used in obtaining soil samples is shown in figure 1. The holder consists of a $\frac{1}{4}$-inch iron rod, the upper end of which is bent in the form of a circle. For the standard canvas bag used by the Bureau of Chemistry and Soils, U. S. Department of Agriculture, a circle with an inside diameter of $3\frac{1}{2}$ inches is satisfactory. Four small holes are drilled in the rod at equal intervals and in each is fastened a nail or $\frac{1}{8}$-inch by 1-inch bolt, sharpened and bent to form a curved hook whose point extends about a half inch toward the center and about a half inch above the top of the circle, as shown. The lower end of the straight part of the rod is pointed for ease in pushing it into the ground. A rod about 40 inches long is convenient. The holder is pushed into the ground near the point where the sample is to be taken and the bag is inserted into the circle from the bottom until the upper edges are about half an inch above the hooks, which are then pushed through the cloth at the upper part of the bag. The sample bag is thus held open at a convenient height for filling, and the operator's hands are free to examine the sample extracted with the soil auger.

Other arrangements, using three, five and six hooks, have been tried but offer no advantages over the number recommended, since increasing the number requires more time in placing the bag with but little gain in size of opening. Small, sharp hooks do not damage the bag appreciably.

Several experimental designs using spring arrangements instead of hooks were made, and although some of them might be superior if of factory design, they are much more difficult to make and adjust with the materials available in the average laboratory.

The holder has been found especially useful in taking composite samples from a small area, as the bag need not be removed from the holder until it is filled. The use of more than one holder, identified by distinctive color, greatly reduces the possibility of error in taking composite samples at different depths.

[1] Associate soil technologist.

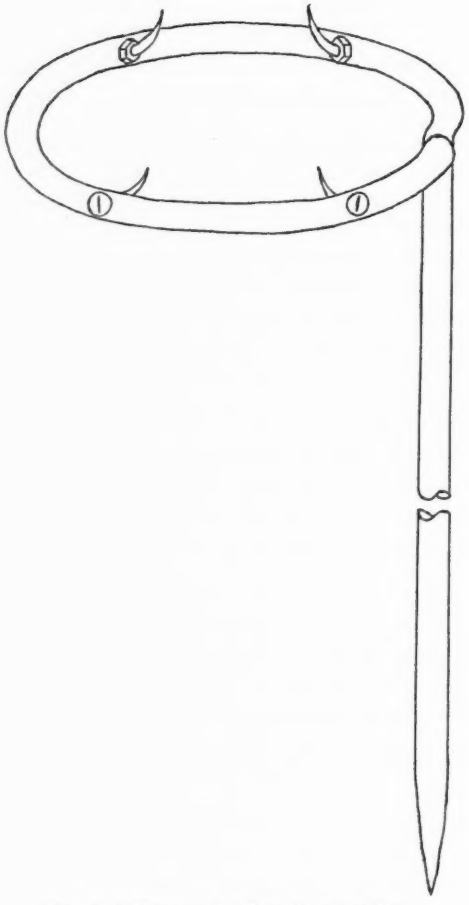

FIG. 1. A HOLDER FOR SOIL SAMPLE BAGS

THE NITROGEN CONTENT OF THE SOIL AS RELATED TO THE PRECIPITATION-EVAPORATION RATIO

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Received for publication September 3, 1929

In a discussion on climatic factors and soil nitrogen by the author (7) the following equation was given:

$$N = f(T, H) \qquad (A)$$

where N represents the total nitrogen content of the soil; T, the air temperature; and H the humidity factor, that is, the ratio of precipitation to evaporation. Temperature and moisture must be treated as two independent variables so that in correlating soil nitrogen with one of those factors, the other must be kept constant. In two previous papers (7, 8) moisture was kept constant and the so-called *nitrogen-temperature relationship* was investigated. A study of the *nitrogen-moisture relationship* in regions of equal temperature is still to be made in order to clarify further the effect of the climate upon the nitrogen content of the soil. The presentation of several soil nitrogen-moisture curves is the main object of this paper.

The influence of climate on the formation of humus in the soil was discussed by Lang (11) in 1920. Regarding the rôle played by moisture, he says, "The more humid a region, the greater the amount of organic matter produced by vegetation, but the smaller the decomposition by microörganisms, hence the humus content of the soil increases with increasing moisture." No data or graphs to illustrate this important conception are given.

An attempt to correlate quantitatively the soil organic matter with climate, was undertaken by Smolik (17). He analyzed the humus of numerous samples of degraded chernozem and podsolized soils from Czechoslovakia, and correlated the results with Lang's rain factor (precipitation divided by temperature). According to Smolik's data, which are summarized in table 1, the amount of total humus (total organic matter) shows no variation with the rain factor, whereas the chemical composition of the humus indicates a climatic relationship.

In a study on alpine vegetation and soil formation, the author (6) drew a

[1] The author is indebted to Prof. F. L. Duley (Kansas), Prof. A. W. Blair (New Jersey), Mr. A. T. Sweet (Colorado), and T. M. Bushnell (Indiana) for obtaining soil samples and nitrogen analyses.

humus-moisture curve based on N.S. Quotients[2] (precipitation divided by absolute saturation deficit of air). This was found to be of exponential nature; but the number of points was not great enough to make the curve very significant.

Sievers and Holtz (16), also working in mountain regions, found that soil nitrogen and organic matter increase with a higher altitude and its correspondingly higher precipitation. Some of their interesting figures are given in table 2.

TABLE 1

Chemical composition of humus and climate

(After Smolik)

LOCATION	RAIN FACTOR (ANNUAL)	AMOUNT OF HUMUS		CHEMICAL COMPOSITION OF TOTAL HUMUS				
		Total	Colloidal	C	N	H	C:H	C:N
		per cent	*per cent*	*per cent*	*per cent*	*per cent*		
Hulin	53.1	3.78	2.11	35.4	1.6	8.5	4.2	22.2
Slapanice	70.9	3.23	1.35	28.6	1.2	9.8	2.9	23.1
Radomin	91.1	3.55	0.76	19.6	0.7	10.9	1.8	29.9
Frenstat	144.1	3.45	1.14	17.1	0.8	10.9	1.6	21.0

TABLE 2

Variation of soil organic matter with altitude in fine-textured soils of the arid regions of the State of Washington, U. S. A.

(After Sievers and Holtz)

ALTITUDE	ANNUAL PRECIPITATION	TOTAL N IN SOIL	CARBON : NITROGEN RATIO
feet	*inches*	*per cent*	
1,050	7.5	0.054	12.7
1,050	8.5	0.052	10.7
1,400	10.0	0.083	12.1
1,400	12.0	0.091	12.4
1,565	12.5	0.060	11.0
1,560	15.5	0.106	10.6
1,525	16.0	0.082	13.4
1,600	16.5	0.092	13.3
1,800	17.0	0.108	13.4
2,550	21.5	0.202	12.9

One of the best curves published along this line of investigation is that of Russell and McRuer (14), who correlated the nitrogen content of virgin Nebraska soils with annual rainfall. The relationship is perfectly linear, but after the authors reduce the soils to a common hygroscopic coefficient, in order

[2] N.S. is an abbreviation for Niederschlag and Sättigungsdefizit. In English and French we would use the term P. S. Quotient.

to eliminate the texture variations, the relationship becomes non-linear. Fortunately Russell's curve is nearly free from the common mistake in studies of soil moisture relationships; namely, the failure to compare only regions of constant temperature. Whether or not the results in tables 1 and 2 are appreciably influenced by differences in temperature cannot be said, but even the use of the rain factor or the N. S. Quotient does not take account of the temperature effect itself.

HUMIDITY FACTOR MAPS OF THE UNITED STATES

At the outset, one must decide on the moisture value to be used. Apparently rainfall alone is not a satisfactory bases for climatic moisture-divisions

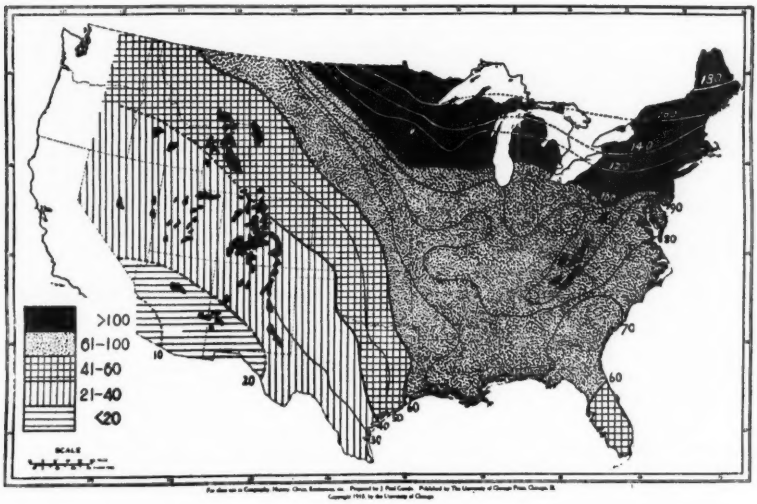

FIG. 1. MAP OF RAIN FACTORS (PRECIPITATION-TEMPERATURE QUOTIENTS) OF THE UNITED STATES

The rain factor is only a fair substitute for the precipitation-evaporation ratio, but can be calculated for most of the meteorological stations and is helpful for orientation purposes.

because of the great variations in the evaporation rates, irrespective of rainfall, which offset the effect of the precipitation. A glance at the evaporation map published by the Weather Bureau (10) shows that in the warm season alone (April to September) evaporation varies from 25 to 88 inches in various parts of the United States.

The necessity of including evaporation in moisture studies has long been recognized by American botanists. Transeau (12, 19) was the first to construct a precipitation-evaporation map of the eastern United States. This map was based on T. Russell's evaporation measurements made during 1877–

78 (15). Transeau's map might have been used for the present study, except for two reasons: first, the map of Transeau rests on evaporation measurements of one year only, and second, the map cannot be compared with humidity factor maps of other countries, because of differences in observational methods. An adequate substitute, therefore, had to be found.

Lang (11) suggested the so-called rain factor (RF) in which the evaporation is replaced by temperature, because, for the magnitudes in question, the vapor tension is nearly a linear function of temperature. Following Lang's suggestion, rain factors were calculated for the present study for over 2,000 meteorological stations by using the data collected by the U. S. Weather Bureau

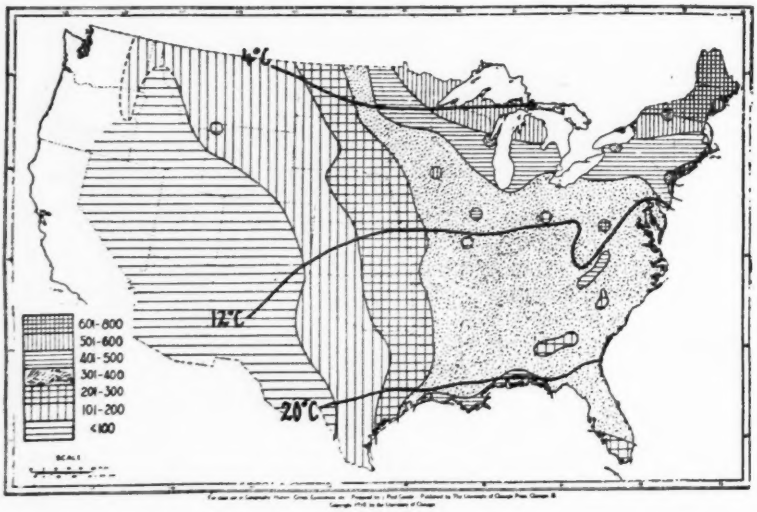

FIG. 2. HUMIDITY FACTOR MAP (N.S.Q.) OF THE UNITED STATES AND ANNUAL ISOTHERMS OF 4°, 12°, 20°C.

The N. S. Quotient is a satisfactory substitute for Transeau's precipitation-evaporation ratio and has the advantage of international application.

(20). A rain factor map of the United States is given in figure 1. A similar world map was previously designed by Hirth (3).

A further step in obtaining evaporation substitutes was made by A. Meyer (13), who argued that not only temperature but also air humidity regulates the evaporation magnitudes. He formed the so-called N.S. Quotient (precipitation: abs. saturation-deficit of the air). Because Meyer published an N.S.Q. map for Europe only (9, 13), a corresponding map of the United States had to be drawn. It is based on 144 N.S. Quotients and has exactly the same shading (fig. 2) as Meyer's map of Europe. A detailed table of all American values for precipitations, rain factors, and N.S.

Quotients, together with a critical, comparative discussion was previously given by the author (9). A graphical comparison of these values is given in figure 3. When one remembers that Transeau's ratio consists of evaporation measurements for a single year only, whereas the N.S. Quotients include 20 to 50 years of air humidity measurements, it is probably safe to conclude that

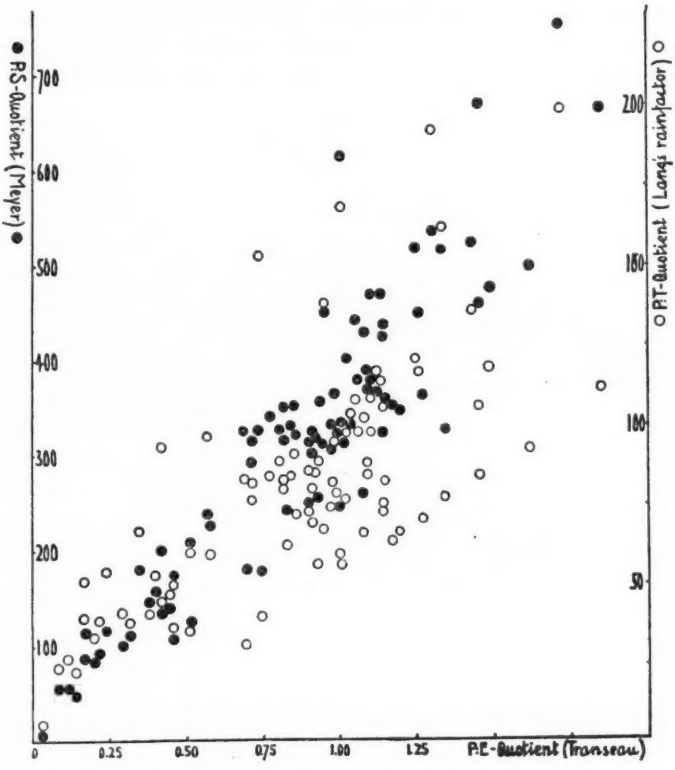

FIG. 3. GRAPHICAL COMPARISON BETWEEN PRECIPITATION-EVAPORATION QUOTIENT OF TRANSEAU, PRECIPITATION-SATURATION DEFICIT QUOTIENT OF MEYER (N.S.Q.) AND PRECIPITATION-TEMPERATURE QUOTIENT OF LANG (RAIN FACTOR)

the diversion of the N.S.Q. points from a perfectly straight line is due to the incompleteness of Transeau's data. Averages of repeated evaporation measurements would undoubtedly reduce the scattering. In other words, the N.S. Quotient seems to furnish a satisfactory substitute for the true precipitation-evaporation ratio.

METHOD

In the present study 628 nitrogen analyses (6 to 8 inches of surface soil) were correlated with N.S. Quotients. The values used were drawn from three sources: (*a*) soil samples from Missouri and Kansas which were collected by the author and analyzed at the Missouri experiment station, (*b*) soil samples obtained from Colorado, Kansas, and New Jersey through the soil surveyors of the respective states but analyzed at the Missouri experiment station, and (*c*) soil analyses from Illinois, Texas, Ohio, Indiana, Louisiana, and Mississippi (1, 4, 5, 18, 21), taken from soil bulletins or received through private

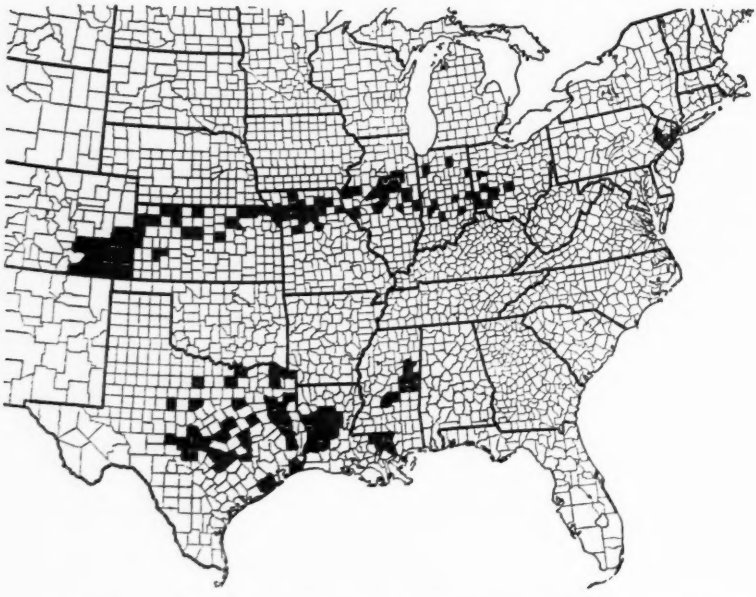

FIG. 4. MAP SHOWING THE LOCATION OF THE COUNTIES FROM WHICH SOIL NITROGEN ANALYSES WERE OBTAINED

communication. As in previous work, the nitrogen analyses of each county, ranging from 2 to 18, were averaged separately. This average was taken as the comparable unit and plotted in figures 5 and 6. To simplify the mathematical treatment, N.S.Q.-class intervals were formed and their nitrogen averages only were tabulated. In order to exclude variations in soil texture and topography, the investigation was restricted to loams and silt loams of gentle rolling upland soil types.[3]

The counties were selected from two different regions, a temperate region

[3] The flat prairies, for example, Putnam silt loam, were excluded.

TABLE 3

Nitrogen-humidity factor relation in the temperate region

(Annual temperature 11°C.)

STATE	ANNUAL HUMIDITY (N.S.Q.) FACTOR		MEAN ANNUAL RAINFALL[1]	NUMBER OF COUNTIES		NUMBER OF N VALUES		AVERAGE TOTAL N CONTENT OF GRASSLAND SOILS			AVERAGE TOTAL N CONTENT OF TIMBER SOILS (OBSERVED)
	Class interval	Mid-point		Grass-land	Timber	Grass-land	Timber	Observed	Calcu-lated	Difference	
			inches	*units*	*units*						
Colorado	50–100	75	12	4	—	13	—	0.082	0.072	+0.010	—
Colorado Kansas	100–150	125	12–15	9	—	27	—	0.112	0.111	+0.001	—
Kansas	150–200	175	15–20	4	—	10	—	0.127	0.143	−0.016	—
Kansas	200–250	225	20–25	4	—	10	—	0.184	0.171	+0.013	—
Kansas Missouri	250–300	275	25–30	6	2	39	7	0.205	0.194	+0.011	0.110
Missouri Illinois Ohio	300–350	325	30–42	9	15	65	33	0.207	0.214	−0.007	0.118
Missouri Illinois Indiana Ohio	300–400	375	30–45	13	23	21	73	0.222	0.230	−0.008	0.117
New Jersey	400–450	425	45–47	—	3	—	11	—	—	—	0.138
New Jersey	450–500	475	47–51	—	4	—	5	—	—	—	0.140

TABLE 4

Nitrogen-humidity factor relation in the subtropical region

(Annual temperature 19°C.)

STATE	ANNUAL HUMIDITY (N.S.Q.) FACTOR		MEAN ANNUAL RAINFALL	NUMBER OF COUNTIES		NUMBER OF N VALUES		AVERAGE TOTAL N CONTENT OF GRASSLAND SOILS			AVERAGE TOTAL N CONTENT OF TIMBER SOILS		
	Class interval	Mid-point		Grass-land	Timber	Grass-land	Timber	Observed	Calcu-lated	Difference	Observed	Calcu-lated	Difference
			inches	*units*	*units*								
Texas	100–200	150	22–40	6	13	44	69	0.083	0.073	+0.010	0.058	0.050	+0.008
Texas Louisiana	200–300	250	35–55	6	20	13	139	0.095	0.092	+0.003	0.046	0.050	−0.004
Louisiana Mississippi	300–400	350	50–64	5	8	19	30	0.096	0.101	−0.005	0.052	0.050	+0.002

with annual temperatures ranging from 51 to 53°F. (10.6 to 11.7°C.) and a subtropical region with annual temperatures of 64 to 68°F. (17.8 to 20.0°C.), as shown in figure 4. The humidity factor (N.S.Q.) for each county was obtained in the following manner. In a system of coördinates, with meridians as abscisse and N.S.Q. as ordinate, the N.S.Q. of meteorological stations lying around the isotherms mentioned, were plotted and connected by a smooth line. The humidity factor (N.S.Q.) of each county was then determined graphically from this line on the base of its average meridian.

The assembled nitrogen values of each county are shown in figure 5 and 6 and a summary of the nitrogen averages of the N.S.Q. classes is given in tables 3 and 4. In each temperature region two different, well-defined lines are evident; namely one for grassland soils, and one for timber soils.

MATHEMATICAL FORMULATION

There are numerous equations existing which would satisfactorily describe the regularly ascending curves as given for the grassland soils. Preference goes to an equation which gives a simple and significant first differential coefficient. The similarity of the curves to the well-known formula of Mitscherlich is obvious. Mitscherlich's logarithmic curve with decreasing increments, quite common in growth processes, has the form:

$$\frac{dN}{dH} = k\,(A - N) \qquad (B)$$

or integrated and under the assumption that $N = 0$, if $H = 0$:

$$N = A\,(1 - e^{-kH}), \qquad (C)$$

where N is the total nitrogen content of the soil in per cent, H is the humidity factor (N.S.Q.), and A, k, e, are constants. For the two experimental grassland curves the equations are

$$N_{11^\circ} = 0.320\,(1 - e^{-0.0034\,H})_0^{400} \qquad (D)$$

$$N_{19^\circ} = 0.110\,(1 - e^{-0.0073\,H})_0^{400} \qquad (E)$$

The index of N refers to the isotherm for which the equation holds. The close agreement between calculated and observed values for the class averages is shown in tables 3 and 4. It is well to keep in mind that the nitrogen lines (fig. 5 and 6 and equations D, E) are mainly of fictive value. They represent the trend of the averages; although, for natural conditions one might better think in terms of nitrogen "bands" as indicated by the white points scattered around the mathematical line. It seems that these bands vary in width and become broader as one goes north. In the nitrogen-temperature relation previously cited, it was found that the mean error of the class averages—which

might be taken as an index of the width of the band—increases considerably from the Gulf States to Canada.

In the case of the nitrogen-humidity factor relation in timber soils, it was quite contrary to expectations to find that the nitrogen values in the south are grouped around a straight line, parallel to the abscissa (fig. 6). This leads to the suggestion that the nitrogen content of the subtropical timber soils investigated, is independent of the climatic moisture conditions, at least between N.S.Q. 100 and 400. Apparently, high temperature keeps the nitrogen content of these subtropical soils on such a low level that climatic moisture conditions become of subordinate importance in soil nitrogen maintenance.

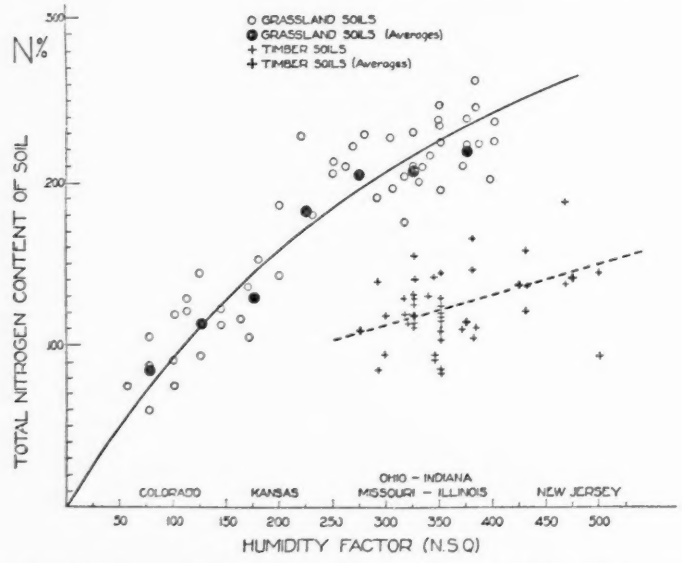

FIG. 5. SOIL NITROGEN-HUMIDITY FACTOR RELATION ALONG THE ANNUAL ISOTHERM OF 11°C.

White points and light crosses represent county averages; black points and heavy crosses, nitrogen averages of N.S.Q.-class intervals.

The line connecting the nitrogen averages for the timber soils has the simple mathematical expression

$$N_{1\phi^*} = \text{constant, namely 0.05 per cent} \qquad (F)$$

In the temperate region the trend of the timber soil curve is not so obvious. The dispersion of the county averages (light crosses in figure 5) is too great to justify any suggestion of a definite mathematical equation.

INTERPRETATION OF THE CURVES

The curves show a relative maximum of soil nitrogen in semi-arid and semi-humid regions. This considerably higher nitrogen content of semi-arid soils over humid soils is a well-known fact, but the cause is unknown to many soil scientists. Lang would attribute the abnormal peak to the high lime content of semi-arid soils, which, as he believes, retards the decomposition process of the organic matter. Another explanation of the phenomenon is suggested from both figures 5 and 6. It is probably not the mere lime content of the soil, but rather the nature of the native vegetation which brings about the sudden drop in soil nitrogen as one passes from

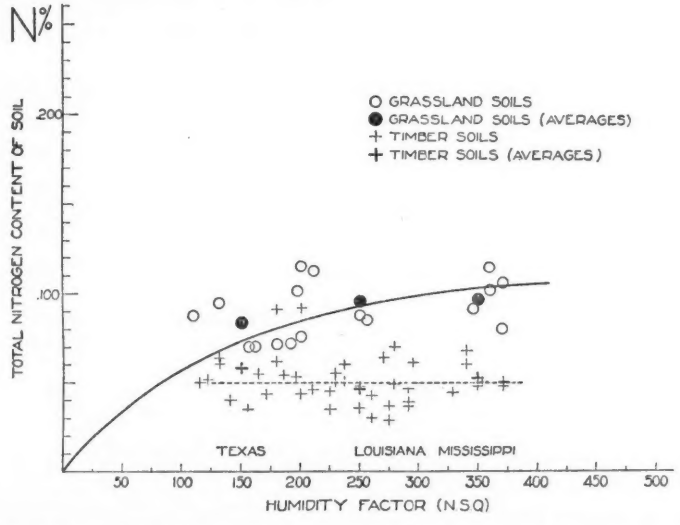

FIG. 6. SOIL NITROGEN-HUMIDITY FACTOR RELATION ALONG THE 19°C. ANNUAL ISOTHERM

White points and light crosses represent county averages; black points and heavy crosses, nitrogen averages of N.S.Q.-class intervals.

semi-arid to humid regions. The highest nitrogen and organic matter values (in the surface soil) do not occur in the chernozem-like soils of central Kansas, which are neutral and contain lime in the subsoil; they are to be found in the slightly acid prairie soils of Missouri, Illinois, and Indiana, where the carbonates have been leached.[4] On the other hand, the neutral timber soils of Missouri and eastern Kansas (Knox silt loam), which have lime in the subsoil, are very low in nitrogen; even lower than the acid timber soils of New Jersey. That part of the graph in which grassland and timber overlap—the so-called transition region (12) or forest-steppe (2)—is of special significance.

[4] In agreement with Russell's observations in Nebraska (14).

On the same parent material, at the same humidity factors and temperatures, one finds that the nitrogen content of the soil may vary a hundred per cent, depending simply on whether the soil sample originates from native prairie or native timber land. Of course, limestone soils are generally higher in organic matter than non-limestone soils, which might partly account for the considerable variation of nitrogen within prairie and timber soils themselves. However, the great difference between humid soils and slightly arid soils is explained more simply on the bases of differences in vegetation.

Thus, an essential difference exists between the nitrogen-humidity factor relation and the nitrogen temperature relation (8) in the United States. The nitrogen temperature relation is a *continuous* function, always decreasing from north to south, at a rate which is proportional to the soil nitrogen content itself; whereas the nitrogen humidity factor relationship is a *discontinuous* function, showing a marked break in the semi-humid region.

The fact that the grassland nitrogen relationship can be described by Mitscherlich's logarithmic curve is of theoretical and practical interest, but the physiological certainty remains to be established. It is possible that the fixation of nitrogen is governed by Mitscherlich's law. On the other hand, it should be observed that a similar logarithmic curve can be obtained by plotting the yields of prairie hay to an acre of each county against the humidity factors. This fact points toward the conclusion that soil nitrogen and soil organic matter stand in close relation to the amount of organic matter produced by vegetation. These, however, are merely suggestions and cannot yet be assumed as established.

TABLE 5

Values of the C : N ratio along the 11°C. isotherm

N.S.Q.	STATE	CARBON-NITROGEN RATIO	VEGETATION
200–300	Kansas	11.15 ±0.470	Grassland
	Nebraska	11.90 ±0.383	
300–400	Illinois	11.79 ±0.229	Grassland
		11.03 ±0.272	Timber
400–600	New Jersey	10.82 ±0.250	Timber

THE CARBON-NITROGEN RATIO

Although the total nitrogen content of the soil varies with humidity factors, it is an essential fact that the carbon-nitrogen ratio remains fairly constant along the 11°C. isotherm as seen from table 5. The average C:N ratio has a value of about 11.3 and is nearly the same both in timber (10.9) and grassland soils (11.6). It will be remembered that the ratio varies with temperature (8),

being wider in the North than in the South. These two statements do not necessarily contradict each other, because we are dealing with two independent variables, moisture and temperature.

SUMMARY

1. A study was made to ascertain the relation between N.S. Quotients (e.g. substitute for the true precipitation-evaporation ratio) and total nitrogen content of soils in regions of equal temperature.

2. The two isotherms selected belong to the *temperate* region (annual temperatures 51 to 53°F.) including territory in Colorado, Kansas, Missouri, Illinois, Indiana, Ohio, and New Jersey, and to the *subtropical* region (annual temperatures 64 to 68°F.) in the states of Texas, Louisiana, and Mississippi.

3. In both regions the average nitrogen content of grassland soils increases logarithmically with humidity factors (N.S. Quotients) while the nitrogen content of subtropical timber soils is not influenced by humidity factors.

4. The nitrogen-humidity factor relationship is a discontinuous one, consisting of two separate curves, one for grassland soils and one for timber soils.

5. In the temperate region the carbon-nitrogen ratio does not vary with the humidity factors. Its average value is about 11.3.

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PLANT-FOOD REQUIREMENT OF RICE[1]

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In a previous paper (5) the writer gave accounts of an investigation designed to determine the minimum requirement of various essential elements by some agronomic plants. Although it is obviously necessary for plants to absorb certain elements in order to grow, nevertheless, plants may absorb more than they require, hence certain quantities of given elements in the plant, although essential in nature, may be considered as having been absorbed as the effect of growth, rather than as the cause thereof.

In this paper, growth is defined and expressed by weight. Chemical analysis of a plant gives the weights of the various elements and compounds that compose it. In a sense, then, it is the segregation of total growth into its component units—the weight of each constituent element. Growth therefore as here expressed is the sum of the weights of all elements contained in a plant, and variation in the composition is that of different ratios of the quantities of any given element or elements absorbed to the weight of the whole. Obviously as elements are absorbed they superimpose on the weight of the absorbing plant that of their own mass and consequently produce an increase in the weight of the plant and also an alteration in its composition. Although the absorption of any quantity of an element is growth, in the sense that it makes for increase in weight of plant, nevertheless, the phenomenon does not define growth in a specific way. It does not define growth in terms of the quantity of element in its rôle of a limiting factor. The problem set in this investigation was to distinguish growth caused by a given quantity of an essential element absorbed in the early growth period, from that growth associated with the absorption of the element during the entire life of the plant.

This paper deals with experiments with rice which were essentially similar to those carried out with wheat. It was designed to distinguish between the total quantity of an element that may be contained by rice plants and that quantity which is, in a specific and unique way, cause for growth. Thus the total quan-

[1] This experiment with rice was carried out in 1926 and 1927. In the August, 1929 (volume 28, no. 2) issue of SOIL SCIENCE, R. P. Bartholomew reports in an investigation—The Availability of Nitrogenous Fertilizers to Rice—that rice plants can utilize nitrates under certain conditions. The writer's experiments touching this point are in full agreement with those given by Mr. Bartholomew.

tity of an element absorbed by the plant was to be differentiated into two parts —a fraction that caused growth and one that did not.

The actual requirement by rice of any element is determined by the maximum production of the mature plant and of its properly differentiated products—grain, straw, roots—obtainable for each unit quantity of the element absorbed. Obviously this maximum production also defines the minimum percentage of the element that can exist as a constituent part thereof. However, an element that is necessary for the growth of a plant as a whole, may or may not be a constituent part of a given plant product; for example, iron in the hulled rice grain is practically absent.

It is not necessary for the determination of the actual salt requirement of a plant to obtain maximum production for a unit area or volume of land, or of culture medium. The problem does not involve any particular yield as a goal in itself; it involves only the evidence that the particular yield in question is the largest that a given amount of an element can produce. The evidence of maximum production of plant for a unit quantity of element absorbed is found in the identity of the minimum percentages of the element in the smallest and in the largest yield for a unit area or volume of growth medium. Or the evidence can also be found in the identity of the percentages of the element in a series of yields expressing a simple multiple relation to the amounts of the given element absorbed.

Planting rice seedlings in a complete nutrient solution and allowing them to grow in such a medium for specific varying lengths of time, and until they obtained to given varying magnitudes of growth, permitted the cultures to absorb varying quantities of given elements. It is known that diversity in the properties of a nutrient solution may affect the aforementioned two types of plant response; that is, it may produce variations in the amounts of any given element absorbed and also differences in the mass of growth made by plants from a given quantity of that element.

In order, then, to obtain the maximum production of plant for a unit quantity of an element, or its corollary, the minimum percentage of the element in the mature product, it is necessary to observe certain conditions in the experiments. These are: (*a*) The given quantity only shall be allowed to function in growth. (*b*) The plant must be allowed sufficient time to utilize that given amount of material (thus the plant needs to grow to maturity), but at maturity it must have utilized all of that given material. This imposes a further condition, namely, that the given quantity of material must be absorbed in the early growth stages, and before a development is attained that would preclude complete utilization of the element. The experiments here detailed were designed to meet these conditions.

EXPERIMENTAL

The following nutrient solutions used were prepared from distilled water and Baker's C. P. salts:

1. Nutrient solution minus potassium — $Ca(NO_3)_2$, $MgHPO_4$, $MgSO_4$; 2. Nutrient solution minus calcium — KH_2PO_4, KNO_3, $MgSO_4$; 3. Nutrient solution minus iron — KH_2PO_4, $Ca(NO_3)_2$, $MgSO_4$; 4. Nutrient solution minus magnesium — KH_2PO_4, $Ca(NO_3)_2$, $CaSO_4$; 5. Nutrient solution minus phosphorus — KNO_3, $Ca(NO_3)_2$, $MgSO_4$; 6. Nutrient solution minus nitrogen — KH_2PO_4, $CaSO_4$, $MgSO_4$; 7. Nutrient solution minus sulfur — KH_2PO_4, $Ca(NO_3)_2$, $MgHPO_4$; 8. Complete nutrient solution — KH_2PO_4, $Ca(NO_3)_2$, $MgSO_4$.

All of the preceding nutrient solutions were composed of equal fractional mole concentrations of the salts indicated, and were of osmotic value equal to approximately one atmosphere pressure. The H-ion concentration of these different nutrient solutions varied between pH 5.7 and 6.7. Wherever adjustments had to be made to obtain those values, reagents were used that did not introduce ions other than those indicated in each of the respective combinations given above. Although it was not known whether rice required boron and manganese, it was deemed advisable to add small quantities of these elements to the various culture media; the amount added was 1 p.p.m. of each element.

The rice used was of the low land variety "Caloric." The seed was germinated in tap water, and when the seedlings were about 5 cm. high, they were set into containers filled with the complete nutrient solutions. Every three days for the first three weeks 5 cc. of a .5 per cent solution of ferric tartrate was added, then the applications of iron were made at weekly intervals. It appeared that application of iron to these nutrient solutions needed to be more frequent for young rice plants than for the cereals—wheat, barley, rye, and oats —tested in similar experiments.

At intervals of two weeks, but beginning with seedlings grown four weeks in the complete nutrient solution, plants were transferred from this medium into culture media devoid of one of the elements, as already indicated. The containers were 2-quart or 4-quart Mason jars. Only one plant was used to a jar, but each treatment was duplicated four to six times. Qualitative tests of the culture solutions, made at intervals, showed that no element was exhausted or had become deficient in the media. No replenishment of any element except iron was found necessary. Water was added as required. There were no renewals of solutions, and the plants, once set in their respective containers, grew to maturity in due season. The transfer from the complete to the partially complete nutrient solutions was the only change or renewal of solutions made.

The production obtained from the various treatments is given in table 1.

Table 1 and plates 1, 2, and 3 show that rice can be grown successfully to maturity in various kinds of nutrient solutions. In fact, the weights of many of the individual plants in these experiments were equal to those of representative plants grown in the field which produced large crops. This held, even though the yield of grain, as will be explained later, was not large for each plant.

As the results of other investigators on the nutrition of this plant are, in some important aspects, markedly different from those obtained by the writer, the

TABLE 1

SOLUTION DEVOID OF	AVERAGE WEIGHT OF INDIVIDUAL PLANTS			
	Straw	Roots	Grain	Total
A. Dry weight of rice grown initially 4 weeks in complete nutrient solution and subsequently transferred, for completion of growth, into culture solutions devoid of elements as indicated				
	gm.	gm.	gm.	gm.
K	9.4	3.2	.5	13.1
Ca	16.5	2.5	3.1	22.1
Fe	2.7	.4	...	3.1
Mg	29.5	10.8	3.0	43.3
P	14.1	3.2	5.9	23.2
N	2.5	1.0	.5	4.0
S	32.0	6.0	.5	38.5
B. Grown 6 weeks in complete solution, and then transferred as indicated above				
K	11.8	2.4	1.0	16.2
Ca	19.2	1.8	2.8	23.8
Fe	6.0	1.5	...	7.5
Mg	31.2	6.5	3.7	41.4
P	28.3	7.0	5.1	40.4
N	4.6	2.3	.8	7.7
S	28.6	4.4	4.0	37.0
C. Grown 8 weeks in complete solution and then transferred as indicated above				
K	13.3	2.6	1.9	17.8
Ca	24.1	3.7	3.0	30.8
Fe	12.2	1.5	...	13.7
Mg	23.7	5.2	3.5	32.4
P	24.6	5.1	4.0	33.7
N	7.3	2.5	.8	10.8
S	20.4	4.8	2.5	27.7
D. Grown 10 weeks in complete solution and then transferred as indicated				
K	14.0	2.5	2.0	18.5
Ca	20.1	2.6	3.1	25.8
Fe	13.0	1.7	...	14.7
Mg	29.3	5.9	3.0	38.2
P	18.0	3.6	3.5	25.1
N	9.1	1.3	.8	11.2
S	19.8	3.7	3.0	26.5
E. Dry weight of rice grown to maturity in complete nutrient solution				
	26.6	3.3	3.0	32.9
F. Grown 8 weeks in complete nutrient solution and then transferred into solution of KNO_3				
	19.3	4.3	3.0	26.6
G. Grown 8 weeks in complete nutrient solution and then transferred into a solution of $Ca(NO_3)_2$				
	12.7	1.8	1.6	16.1

apparently prevailing view as to some of the nutritional characteristics of the plant are cited:

1. Rice has been considered to require an ammonium salt in addition to nitrates. It was held that the plant would not thrive on nitrates as the only form of nitrogen. No ammonium salts were used in the nutrient solutions here employed

2 The plant has been described as one that required nutrient media of lower concentrations of solutes than do other cereals. The nutrient solutions used in these experiments were compounded according to the formulas used for wheat, as already noted, and all of these solutions must be considered as fairly concentrated.

3. The plant has been described as having a high water requirement. Although no measurements were taken of the amounts of water transpired, the observations made seem to indicate that rice does not require more water than do other cereals grown under similar conditions.

DISCUSSION OF DATA

It is evident, from the data and from the photographs, that for the growth of rice, potassium, nitrogen, and iron are required either in larger quantities, or for longer periods of time, than are other elements. It appears that these three elements play a unique rôle in the nutrition of this plant. On the other hand, the absence of one or more of the elements calcium, magnesium, phosphorus, and sulfur, after initial exposure of the rice plants to the complete nutrient solutions, did not have any pronounced harmful effect on the development. This indicates that none of the last named elements play such an important rôle in the nutrition of rice as do the elements of the first named group. Indeed, the results of these experiments apparently warrant the questioning of the statement or inference that all of the aforenamed elements are essential in appreciable quantities for the growth of this plant. Although the experiments were not planned to raise the question (the experiments were designed in the belief that all of these elements were essential), nevertheless, it appears well, in view of the results obtained, to point out that there is no experimental evidence extant to warrant the assertion that all plants require the same essential elements. Undoubtedly, certain elements are required by all plants, but all plants apparently do not require for their normal development the same essential elements. In the case of rice, the results here obtained indicate that if all of the elements of the second group named were required, some were needed in very small amounts only.

These experiments do show that rice is unique in its nutrition. That the absence of calcium in the culture medium for the length of time indicated was not harmful to rice, apparently places this plant in a different category from that of wheat or other cereals. That the absence of magnesium, phosphorus, and sulfur in the respective solutions for a period equal to about four-fifths of the life of the plant was without harmful effects to its growth, shows the requirement of the plant for these elements to be small (granted that all of them are needed). But if all are needed, it shows that rice has a relatively larger capac-

ity to store sufficient reserve for future need in a shorter period of time than other cereals.

The unique rôle which potassium and nitrogen played in the nutrition of rice undoubtedly is in part due to the requirement of the plant for larger quantities of these elements than of others. The smallest quantity requisite to obtain a specified yield (provided it was utilized to the fullest extent for the production of a crop) would be that expressed by the product of total growth and the minimum percentage of the given element in the mature product. But whether any given quantity of an element would produce the specified yield would depend on the conditions which determine the length of time available for full utilization. The function an element has in growth, apparently must affect the length of time required by the plant to obtain full utilization of a given quantity of the element. The length of time required for a plant to absorb a given quantity sets limitations to the length of the period available for the utilization of the element. The amount a plant can absorb at a given growth period is also dependent on the properties of the growth medium. The progressingly greater yields, then, that were obtained from the cultures exposed for a correspondingly longer time to the complete nutrient solutions, and for a correspondingly shorter time to media devoid of potassium and nitrogen, apparently are explained by the absorption of progressingly larger quantities of these elements. Apparently rice can not store relatively large amounts of either of these elements in its tissue for future use.

Rice has been considered to have a specific need for nitrogen in the ammonium form, but the specificity has been found to vary among varieties. Nagaoka(9) found that upland rice showed less need for ammonium than did lowland varieties. It is not known whether the presence of ammonium salts would have improved the growth of the plants if used in these solutions, but it is evident from the data and from the illustrations that no ammonium salt was needed to obtain large and fully developed specimens of lowland rice in nutrient solutions.

The fact, then, that ammonium nitrogen was not required for normal and large growth of lowland rice in nutrient solutions, together with the fact that in field culture ammonium sulfate is a better source of nitrogen than sodium nitrate, presents the nutrition of this plant as unique in respect to nitrogen. It appears, however, that the diverse results obtained in respect to the use of nitrate and ammonium forms of nitrogen can be explained by factors that affect the availability of iron. The data here given show rice to require available iron in the culture medium longer than any other element. Comparison of the results obtained from the absence in the medium, on the one hand, of iron and, on the other hand, of nitrogen, brings out certain characters of the requirement of the plant for these two elements. Although the absence of nitrogen in the medium after the plants were 1 month old precluded the attainment of large yield, nevertheless it did not preclude normal development of the plants. This is evidenced by the production of grain in all of the minus

nitrogen series. The absence of nitrogen in nutrient solutions, even at the earliest seedlings stage does not preclude reproduction in the plant. But the absence of iron in the growth medium of young rice seedlings caused them to die prematurely. Even the absence of iron from the medium after three months' growth in complete culture solution caused the plants to become progressively yellow, chlorotic, and etiolated; they ceased to grow as the initial steps of these symptoms appeared. The state of development attained at the death of the rice plants exposed to the several series of minus iron nutrient solutions, was determined by the length of time iron was available to them.

When iron was supplied in an available form, rice grew well in all nutrient solutions used containing nitrates as the only source of nitrogen. Iron supplied in an organic form, such as citrate or tartrate, was found to be available to rice in all nutrient solutions in which wheat, oats, or barley was found to thrive. But, iron supplied in an inorganic form, such as $FeSO_4$, $FeCl_3$ or $FePO_4$, became inavailable to rice grown in the nutrient solution in which these forms of iron were found to be available to the wheat, oats, and barley. Now, as the inorganic form of iron has been found to be available to rice grown in nutrient solutions containing ammonium salts, and as rice also thrives in nutrient solutions containing no ammonium salts, provided that iron is supplied in the organic form, it is evident that the availability of this element to the plant is affected by that of other elements in the culture medium. It appears that in the presence of ammonium salts, the inorganic form of iron becomes readily available to rice by virtue of acidity imparted to the solution as a result of the so-called "selective" absorption of nitrogen as a cation. But in nutrient solutions having nitrates as the only source of nitrogen, this element is in the anion form. The "selective" absorption renders the reaction of the medium insufficiently acid or perhaps even alkaline and the consequent effect thereof is to render iron inavailable to rice.

Of the elements essential for the growth of rice, iron appears to be the most important, as judged by the criterion—"length of time an element needs to be available to the absorptive processes of the plant." The fact that iron was required in the culture medium for such a long time indicates one of the following as a possible explanation of the results obtained: (*a*) that the rice plant has small capacity to absorb iron and store it as reserve for future use, hence the need of continual supply of this element in available forms in the culture medium during the greater part of the growing period; (b) that the plant may have the capacity to store relatively large amounts in its tissue, but the character of the sap is such as to render it unavailable for the processes in which it is needed. According to Gile (6), rice has an exceedingly small capacity for the absorption of iron. This is also the conclusion of the writer, arrived at from these experiments. The large amounts of iron noted on the roots of certain cultures, were considered evidence that it does not enter the rice plant readily.

The requirement of rice for potassium appears to be due in part to the property of this element in its relation to the processes of absorption of nitro-

gen. That is, potassium is the ion of opposite charge with which nitrates are most effectively absorbed and utilized by rice. Apparently in the nutrition of rice hydrogen ions belong to the same category as potassium in its relation to nitrogen. This was indicated by the acid reaction of nutrient solution found most suitable for the growth of the plant. But potassium appeared as characteristically a carrier of nitrogen. This was evidenced by the excellent growth obtained from cultures grown in solution of KNO_3, after initial exposure to complete culture media (pl. 3, fig. 2). Cultures exposed to solutions of $Ca(NO_3)_2$ or $Mg(NO_3)_2$ after initial exposure to complete culture media did not in any degree produce the growth obtained in the KNO_3 solution. Thus, these results together with the excellent growth obtained in the culture solution devoid of calcium and magnesium (solutions 2 and 4) but which contained potassium, appear as evidence that rice not only has a specific requirement for potassium, but that the requirement is related to the property of this element. in its relation to nitrogen absorption. Rice undoubtedly would respond similarly to wheat (4), in tests designed to determine how a given anion is paired with an ion of opposite charge. That is, nitrogen absorbed with potassium would produce greater growth of plant than if it were absorbed only with the calcium or with the magnesium ion; it being understood that in such experiments all essential elements are supplied to the plants, but not in the presence of all elements, as is the case in a complete nutrient solution.

The relation of potassium to the absorption and utilization of the ammonium ion by rice is a matter that requires further study. As ammonium is similar to potassium in the character of its charge, the potassium cannot be considered as a "carrier" of the ammonium ion. In view of the results here obtained in the growth of rice in media devoid of calcium, magnesium, phosphorus, and sulfur, after initial exposure to a complete culture medium, a test of the efficacy of the following three solutions—$(NH_4)_2SO_4$, NH_4NO_3, and a mixture of $(NH_4)_2SO_4$ and K_2SO_4 or KH_2PO_4, would probably throw further light on the function of potassium, and especially as it may be related to the absorption of nitrogen.

In this investigation, no tests were conducted to determine the reaction most favorable for the growth of rice. The production obtained from the various nutrient solutions whose reaction was known, however, shows that rice is similar to other cereals in that the reactions of culture media for the initial growth of plants need to be slightly acid. The complete nutrient solution had a pH of 5.7. Although it is probable that a slightly greater acidity of the complete nutrient solution would have given the plants a better start, nevertheless, the yield obtained from the plants subsequently transferred into various culture media whose reaction, though initially slightly acid, was changed perceptibly with the growth of the plants, indicates a wide range of adaptation. The final yields, if indicative of any relation in these circumstances, show that the older the plant becomes, the less sensitive it is to the reaction of the medium. The final range of reaction varied from 4.2 to 7.2 without any corresponding

differences in yield. It appears that the following statement of Copeland (2) is well put: "Rice is not, however, so susceptible to injury by alkalinity as mere consideration of iron alone might suggest."

In the absence of chemical analyses of these plants (which, however, are to be made) it is not known how the composition of the ash varied among the treatments, but it appears that the results obtained from the minus potassium, and also from the minus nitrogen series were predictable from the data on the chemical analysis of rice as given by Herrero (8), Gile and Carrero (7), and Camus (1). The analyses of rice which these authors present show that the amounts of potassium and nitrogen absorbed by the plants are about the same. In no other cereals are the quantities of these two elements so nearly alike as in rice. The agreement of the data, as here obtained, with the character of the ash described in the foregoing apparently can be explained only by the mutual relation of the needs of rice for potassium and nitrogen. Not only does this hold in equality of quantities required, but also in that the absorption of the one is conditioned by the availability of the other.

The chief features of the data on growth of rice obtained in media devoid of one of the elements, calcium, magnesium, phosphorus, and sulfur, can be briefly stated as follows:

1. The greatest tillering was obtained from the cultures exposed to media devoid of magnesium or sulfur.
2. The greatest root growth was obtained in cultures that grew in a medium devoid of magnesium.
3. The cultures with stiffest stalks were those grown in media devoid of calcium or phosphorus.
4. The greatest dry matter production was obtained from the plants that grew in a medium devoid of magnesium.
5. The greatest grain production came from the cultures grown in a medium devoid of phosphorus.
6. The percentage of grain to total dry matter production was less in the cultures devoid of magnesium or sulfur than in the other treatments in which the plants grew normally.

The causal factors which produced these results are not known. Cause is usually considered in terms of positive characters. The absence of an element, therefore, cannot well be considered as cause for an effect in which it did not function. But the absence of a given element in a nutrient solution, and its presence in another, is evidence of two diverse conditions which may cause differences as to the amounts of given elements plants may absorb when thus exposed. Unpublished data from experiments previously made (5), on chemical analyses of the grain, straw, and roots of wheat exposed to treatment similar to that for rice show that the composition of the plants varied markedly according to the character of the culture media in which the plants were placed. Thus the minimum and the maximum percentage of an element that a plant may contain can be obtained at will.

As the method of obtaining the minimum is in essence being described in this

paper, it will not need specific description; but the one used to obtain the maximum needs brief explanation. In order to obtain the maximum amount and percentage of any given element in a normally growing plant (or one that appears normal), it is necessary to exclude from the culture medium for certain periods of growth, elements carrying charges of the same sign as that of the element to be concentrated. Therefore the maximum absorption of any given element by plants cannot take place by continual growth in a so-called "complete" nutrient solution. This is because the electrostatic equilibrium between ions determines the relation of the sums of anions or of cations to the sum of ions of opposite sign which plants absorb from a given nutrient solution. Now as the sum of the charges of the anions equals that of the cations, if it is desired that the plant should absorb a relatively large amount of phosphorus, it is necessary after the actual need of the plant has been met to exclude from the culture medium, elements of the same sign, which, in this case, are nitrogen and sulfur. Thus plants are grown initially in a complete nutrient solution, and subsequently transferred for the completion of growth into media devoid of nitrogen and sulfur. Because nitrate has much greater mobility than sulfate, the absence in nutrient solution of nitrate only will permit the plant to absorb large quantities of phosphorus. The effect of the treatment is to have the element which is to be accumulated in the plant become absorbed in association with all of the elements of opposite sign in the culture medium. As actual growth is also a requirement for absorption of materials, it is necessary that the character of the culture medium at no time be such as to impair the normal development of the plant.

The larger growth of rice obtained from the cultures which were initially exposed to the complete nutrient solution and subsequently to media devoid of one of the elements, magnesium, phosphorus, or sulfur, than that obtained from those plants that grew to maturity in the complete nutrient solution is believed to be due primarily to the effect which the absence of one of the designated elements had upon the absorption of potassium or nitrogen, or both, by the plants.

GRAIN PRODUCTION

The total dry matter obtained from each culture, that is, the weight of single plants, was in many cases equal to that of representative individuals of this variety obtained in the field and yielding large crops. In no case, however, was the amount of grain obtained from a plant in any culture sufficiently large in comparison with the weight of straw produced to be considered representative of a large crop. However, as all cultures developed normally, and all treatments, with the exception of the minus iron series, produced grain, the small yield of grain obtained from each plant needs to be explained by another cause than that of the properties of the nutrient solution.

Several former attempts by the writer to grow rice to maturity in nutrient solutions in the greenhouse failed. At first the plants appeared normal in every

way but after the heads developed, it was found that the panicles contained no grain; the heads appeared at the proper stage of growth, but did not fill. Inspection of the heads showed that many glumes contained pollen long after a growth stage had been attained when normally it should have been emitted. In many cases, it was found that the pollen sacks were not ruptured, even a week or ten days after the flowers had appeared. Study and comparison of the conditions of rice production in the field with those of the greenhouse, gave the suggestion that the failure of the fertilization process to function properly lay in the lack of sufficient humidity in the atmosphere of the greenhouse during pollination. Even though the plants were grown in water, the earthen floor of the greenhouse was kept wet, and the ventilators were open day and night, the atmospheric conditions were adverse to rice production.

The grain produced from these cultures here described was obtained by the following method:

> The greenhouse floor was kept wet and the ventilators, which were opened during the day for aeration and cooling, were closed during the night, the purpose of this procedure being to obtain dew on the rice plants. It was found that if the ventilators were left open during the night, the relatively high humidity which developed in the greenhouse during the day was lost at night by the outward movement of the warm air in the greenhouse. With the ventilators closed during the night, the high humidity developed during the day became dew on the plants at night, as the cool outside temperature caused precipitation of the excess vapor of the greenhouse atmosphere.

Rice apparently requires a saturated atmosphere for proper pollination,[2] and the failure to obtain a large crop of grain from these plants that grew so well in water cultures is, in the writer's opinion, due to conditions of atmosphere, and not of the nutrient solution.

SUMMARY

The results of these experiments show that the actual salt requirement of rice cannot be determined by growing plants to maturity in any so-called complete nutrient solution, however compounded. Furthermore, the results also show that the salt requirement of the plant cannot generally be determined by the amount of elements absorbed, if they are available continually to the growing plant. Under these conditions plants absorb larger quantities of all elements than is required for the growth made. It appears that the conditions which determine the relation between magnitude of yield and that of the absorption of any given element from a culture medium, involve (*a*) the amounts of an element absorbed, (*b*) the length of time required for the plant to absorb the given quantity of an element—obviously this varies with environment and with the nature of the culture medium, (*c*) the length of time required for each of the various elements absorbed to function in growth—that is, to

[2] A paper is to appear on the effect of the diurnal changes in temperature on the development of the rice plant.

become a part of the final product if required therefor, or for a given process in the growing plant if the element is not required as a constituent of a differentiated part of the mature plant.

In the absence of the chemical analyses, it is not known how much of the various elements were absorbed. From the data obtained from other analogous studies, however, it appears safe to assume that the rice grown in the complete nutrient solutions absorbed more calcium, magnesium, phosphorus, and sulfur than did those plants which were initially grown in this medium and subsequently grown to maturity in media devoid of these elements. Espino (3) found that the growth obtained by young rice plants varied somewhat according to the kind of nutrient solution used. His experiments were designed to provide for a series of balances or salt proportions in an array of nutrient solutions. The salts used to supply the required elements were KH_2PO_4, $(NH_4)_2SO_4$, $Ca(NO_3)_2$, and $MgSO_4$. From this experiments, Espino concluded:

> It is safe to say that one very excellent solution would have the potassium, ammonium, and calcium in about the same proportion while the concentration of the magnesium salt would be four or five times as great as any one of the others.

Furthermore, in the experiments with various systematically arranged proportions of KH_2PO_4, $Ca(NO_3)_2$, and $MgSO_4$, in nutrient solution, Espino came to the conclusion that

> . . . . it appears highly improbable that young rice plants could thrive with any three-salt type of solution: There is no doubt that rice requires the cations potassium, calcium, and magnesium, as well as a little ferrum, like other plants, and the ammonium ion cannot be introduced into a three-salt solution without its being the cation of one of the three salts used, which means that its introduction can be accomplished (in a three-salt solution) only by omitting potassium, calcium, or magnesium.

The data here submitted prove conclusively that not only can young rice thrive in nutrient solutions composed of three salts, but that large mature plants can likewise be obtained in such nutrient solutions. Furthermore, as there appears to be a question as to the essential need for the growth of rice of all the aforenamed elements in the quantity usually employed to give measurable physical properties to a nutrient solution, it appears that the conclusions of Espino were based on data which were not fully understood. The fact that excellent growth of rice was obtained in a culture solution that, by inference from the foregoing statements, did not have the properties suitable to obtain good growth of rice, indicates that certain very important principles relating to the salt requirement of this plant were overlooked in the investigations cited.

It appears then, from a study of data on rice culture, that very important factors to be considered in the compounding of nutrient solutions for growth of rice are those which affect the absorption and utilization by the plant of the elements potassium, nitrogen, and iron. Apparently the need of the plant for other elements is not such that would require their presence in nutrient solu-

tion in any particular concentration, or ratios of element to element, as long as the properties of the media do not inhibit the availability of the aforementioned elements. The conditions which affect the availability of the elements of the first group in the presence of those which were not required by the plants in the same degree as the former appears to be the crux of the problem in the salt nutrition of rice. The first element contained in the seed and that which usually becomes the limiting factor of the growth of rice seedlings is iron. Because of what appears to be true—that rice has a low absorptive capacity for iron—the effect of a nutrient solution on the availability of this element becomes a matter of considerable importance. Another matter to be considered in compounding a nutrient solution for the growth of rice bears upon the absorption and utilization of nitrogen and potassium. The apparent greater need of rice for these elements, both as to quantity required and as to the length of time they need to be available, reduces the factors which markedly affect the growth of rice in nutrient solutions, to the conditions that control the availability of iron, nitrogen, and potassium.

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PLATE 1

RICE PLANTS 16 WEEKS OLD GROWN IN NUTRIENT SOLUTIONS OF DIFFERENT SALT COMPOSITION

FIG. 1. Set 1 (from left to right)—Complete nutrient solution; sets 2, 3, 4, and 5—Grown initially 4, 6, 8, and 10 weeks, respectively, in complete nutrient solution, then subsequently grown to maturity in culture solution devoid of potassium.

FIG. 2. Set 1 (from left to right)—Complete nutrient solution; sets 2, 3, 4, 5—Grown initially 4, 6, 8, and 10 weeks, respectively, in complete nutrient solution, then subsequently grown to maturity in culture solution devoid of calcium.

FIG. 3. Set 1 (from left to right)—Complete nutrient solution; sets 2, 3, and 4—Grown initially 4, 6, and 8 weeks, respectively, in complete nutrient solution, then subsequently grown to maturity in culture solution devoid of iron.

FIG. 1

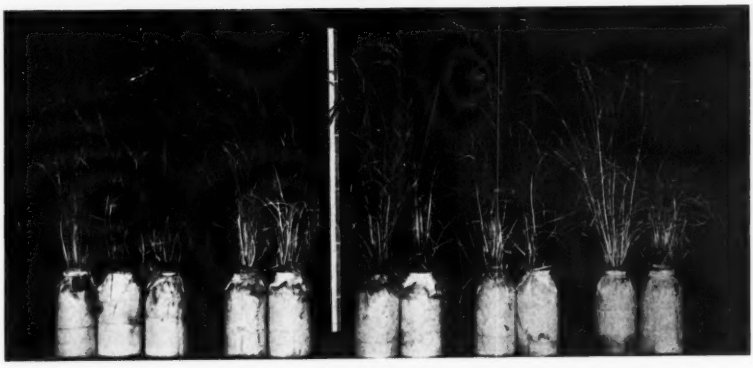

FIG. 2

FIG. 3

PLATE 2

RICE PLANTS 16 WEEKS OLD GROWN IN NUTRIENT SOLUTIONS OF DIFFERENT SALT COMPOSITION

FIG. 1. Set 1 (from left to right)—Complete nutrient solution; sets 2, 3, and 4—Grown initially 4, 6, and 8 weeks, respectively, in complete nutrient solution, then subsequently grown to maturity in culture solution devoid of magnesium.

FIG. 2. Set 1 (from left to right)—Complete nutrient solution; sets 2, 3, and 4—Grown initially 4, 6, and 8 weeks, respectively, in complete nutrient solution, then subsequently grown to maturity in culture solution devoid of phosphorus.

FIG. 3. Set 1 (from left to right)—Complete nutrient solution; sets 2, 3, 4, and 5—grown initially 4, 6, 8, and 10 weeks, respectively, in complete nutrient solution, then subsequently grown to maturity in culture solution devoid of nitrogen.

FIG. 1

FIG. 2

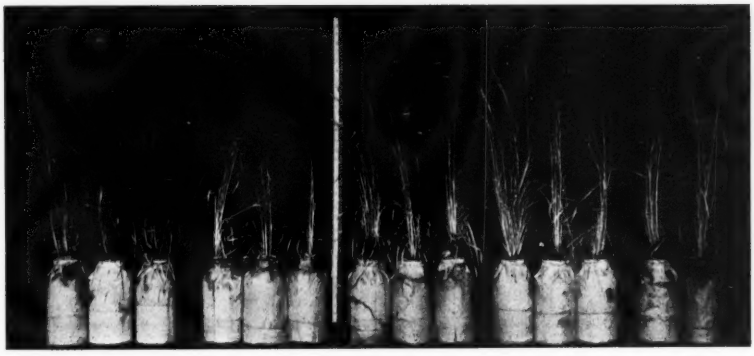

FIG. 3

PLATE 3

RICE PLANTS 16 WEEKS OLD GROWN IN NUTRIENT SOLUTIONS OF DIFFERENT SALT COMPOSITION

FIG. 1. Set 1 (from left to right)—Complete nutrient solution; sets 2, 3, and 4—Grown initially 4, 6, and 8 weeks, respectively, in complete nutrient solution, then subsequently grown to maturity in culture solution devoid of sulfur.

FIG. 2. Set 1 (left to right)—Complete nutrient solution; set 2—Plants grown 8 weeks in the complete nutrient solution and subsequently to maturity in solution of KNO_3; set 3—Plants grown 8 weeks in the complete nutrient solution and subsequently to maturity in a solution of $Ca(NO_3)_2$.

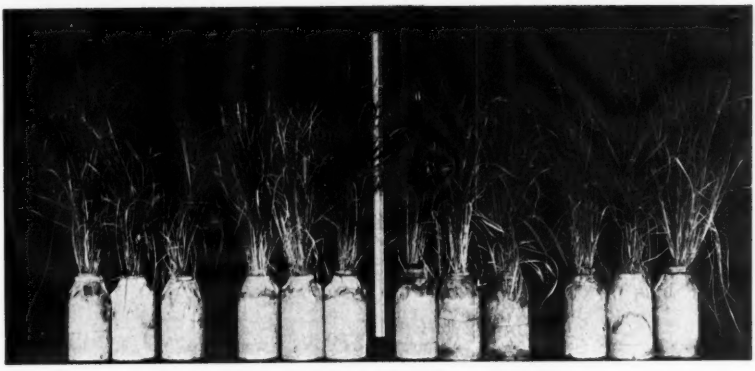

FIG. 1

FIG. 2

SOIL MOISTURE PHENOMENA IN A SATURATED ATMOSPHERE

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In a previous discussion on the mechanics of soil moisture (6) the author made the simplifying assumptions that the soil particles were uniform spheres and that the angle of contact between the water and the spheres was zero. These two assumptions have been made by earlier writers, as referred to in the previous paper.

It is well known that the soil particles are not uniform spheres but present an infinite variety of shapes and sizes. If this were taken into account, the analysis would be infinitely difficult, and therefore spheres are assumed to make an analysis possible.

The other assumption is of a different nature. The angle of contact between the soil particles and the water cannot be determined directly, and thus cannot be shown to be zero, but there is much evidence which indicates that the angle is small if not zero. By zero angle of contact is meant that the meniscus is tangent to the solid surface at the line of contact. This would mean that a drop of water placed on a horizontal glass plate should spread out and cover the entire plate.[3] The fact that this does not occur in most cases and the fact that many other similar phenomena are not wholly reconcilable to the view would indicate that the glass-water contact angle is not only finite but has a value of many degrees. These considerations as well as some direct experiments on soils led workers at the Utah station and elsewhere to doubt the validity of the assumption.

PREVIOUS STUDIES ON ANGLE OF CONTACT

In the latter part of the nineteenth century, Quincke, in a series of articles in the Poggendorf and later in the Wiedemann Annalen, reported his findings to

[1] Graduate assistant, department of physics, Utah Agricultural Experiment Station. The author wishes to thank Dr. Willard Gardner and C. L. Clark for their helpful suggestions during the experimental work and in the preparation of this paper.

[2] Contribution from the departments of physics, soils, and irrigation and drainage engineering. Publication authorized by director, August 30, 1929.

[3] It would cover the plate unless it were so large that the film would have to reduce itself to thicknesses of molecular dimensions.

show the angle of contact to be finite. Early papers gave values as high as 30° for water on glass, and later papers gave smaller, though finite, values. At the same time Magie, Volkmann, and others reported that they found the angle to be zero and gave lack of cleanliness as the cause of finite angles.

Of more recent data several independent experiments have shown the angle to be zero or at most a small fraction of a degree. Most of the experimenters have used glass with water and many organic liquids such as glycerine, olive oil, benzene, chloroform, and ether. To indicate some of the various methods used, three will be considered in some detail.

In 1916, Anderson and Bowen (1) measured the angle of contact of liquids in capillary tubes by determining the radius of the capillary tube and that of the curvature of the meniscus in the center of the tube. The measurements taken with a microscope made use of the apparent displacement of a scratch on the bottom of the vessel, as viewed through the capillary tube when the liquid was introduced. The effect of the index of refraction of the liquid as well as the lens effect of the menisci were considered. The radius of curvature could then be calculated by well-known physical formulas. As the tube used was decreased in size the radius of curvature of the meniscus (assumed to be spherical) approached the radius of the tube. This indicated that the contact angle was small. Mercury was tested and the finite angle of contact was demonstrated by the fact that the radius of curvature of the meniscus remained definitely larger than the radius of the tube.

This experiment was followed by one allowing much greater precision (2). Drops of the liquid to be tested were suspended on a microscope cover glass, held in a vertical plane, with one edge held horizontally. Except at the ends, these long drops would be cylindrical.[4] The effect upon looking through the drop would be that of a cylindrical convex lens at the lower part of the drop, and a part of a cylindrical concave lens above. A narrow beam of light was allowed to pass perpendicularly through the cover glass and drop. At the upper edge of the meniscus the liquid surfaces on the two sides of the cover glass will be parallel if the angle of contact is zero, and the beam will pass through without bending. If the contact angle is finite the two films will not be parallel, but if projected would meet at an angle twice the angle of contact; light on passing through would be bent downwards, as if it had passed through the corner of a prism. The inability of the experimenters to detect any bending with a good optical system showed the angle of contact to be zero, or very small.

Another sensitive test was made by Richards and Carver (7). A piece of glass was set vertically in a vessel filled level full of the liquid to be tested. A narrow beam of light was thrown horizontally and nearly perpendicularly against the glass and the meniscus. The light striking the glass above the meniscus would be reflected horizontally backward. Any point of the meniscus, acting as a cylindrical concave mirror would reflect the light back and upwards at an angle such that it is twice the angle between the tangent to the meniscus at the point in question and the vertical. If the angle of contact is zero, the light reflected from the top of the meniscus would come back horizontally. That from farther down would be reflected upward at a small angle and on. If the angle of contact is finite, then the light reflected from the top of the meniscus would be reflected upwards at an angle. Both by visually following the reflected band of light down to the horizontal and by photographing the reflected light, the angle of contact was shown to be very small if not zero.

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[4] A cylindrical surface does not necessarily have a circular cross-section. In this case the surface would not be a circular cylinder, but all vertical sections perpendicular to the cover glass would be the same size and shape except near the ends.

The "Handbuch der Physik" (3) does not consider the possibility of a finite angle of contact between water and glass and makes the statement that the angle of contact between glass and water is zero and that the water completely covers the surfaces.

EXPERIMENTS ON SOIL MINERALS

This evidence of a zero angle of contact cannot be applied to soils unless several factors are taken into account, some of which are: the glass surfaces and the liquids used were scrupulously clean; evaporation from the menisci had to be reduced to a minimum, usually by a saturated atmosphere; and the solids used were glass and not the substances usually found in soils.

In order to determine the effect of solids other than glass on the angle of contact the author set up an apparatus similar to that used by Richards and Carver. A check test was made with glass after it had been cleaned with hot concentrated sodium hydroxide and then with chromic acid. The angle of contact was zero within the experimental error, which was less than one degree. Then the following rocks and minerals were tested:

Calcite crystal, new cleavage face, and old face cleaned with chromic acid, which only slightly attacked the crystal.
Orthoclase feldspar, new cleavage face, and old face cleaned with chromic acid.
Quartz crystal, face cleaned with chromic acid.
Mica, new cleavage face.
Quartzite and limestone, smooth face ground and polished.

All of the faces so prepared showed a zero angle of contact, and drops of water placed on them spread over the entire surface. Old faces, and cleaned faces after they had been handled, showed finite and widely varying angles of contact.

In the foregoing experiments it was found necessary to keep the surrounding atmosphere saturated. It appeared that the evaporation of the edge of the meniscus deposited slight impurities which caused a finite angle of contact. In experiments with soils exposed to a saturated atmosphere in the dark, this factor should not enter.

EFFECT OF FATTY SUBSTANCES ON THE ANGLE OF CONTACT

The state of "cleanliness" of the soil in nature is very important, and at the same time difficult to determine directly. Many workers have shown that monomolecular films of certain substances, notably fats, oils, and fatty acids, on solid surfaces caused finite angles of contract between water and the prepared surface. Langmuir (5) reports that monomolecular films of oleic acid cause definite angles of contact varying from 18° for mica to 86° for galena. Yet there is not sufficient evidence to show that such films exist on the soil particles in the normal soil.

In order to determine whether there were sufficient amounts of substances in a soil to cause considerable deviations from a zero contact angle, a sample of

Greenville loam was treated with oleic acid. The mechanical analysis being known (4), the surface area of the soil particles could be calculated, and approximately a monomolecular layer was applied by dissolving the correct amount of oleic acid in ether, adding it to the oven-dried soil, and then allowing it to dry slowly, with frequent stirring.

To determine whether the characteristics had been changed, the samples to be tested were placed in vertical glass tubes open at the bottom and standing in water. The height of rise of the water as a function of the time was noted. Two samples of the air-dried soil, one of the oven-dried soil, and one of the oven-dried soil treated with oleic acid were used. The curves are given in figure 1.

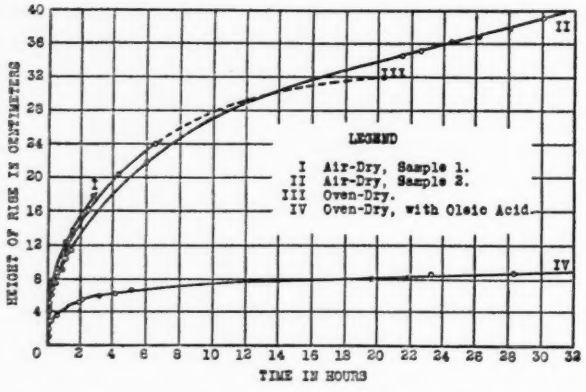

FIG. 1. RATE OF CAPILLARY RISE OF WATER IN TUBES OF SOIL

Curve I is short because 18 cm. was the total height of the soil column. Curve II was continued, and the moisture reached the top of the 53-cm. column after 75 hours; average speed of rise after 30 hours was 7.7 cm. daily. Curve III, showing oven-dried soil, reached the height of the column—32 cm.—during the night; therefore, its position with respect to time is uncertain, but it is some time previous to 20 hours. Curve IV, showing soil with oleic acid, was continued to 292 hours, at which time the water had risen to 13.2 cm. The average speed of rise after 30 hours was 0.34 cm. daily.

It is evident that the oleic acid greatly retarded the speed of rise, and there is every indication that it would not rise as high as the other samples. Thus, it appears that the soil tested in the natural state did not have the characteristics of an oiled surface.

SOIL EXPERIMENTS INDICATING FINITE ANGLES OF CONTACT

One other type of argument has been used against the idea of a zero angle of contact. If a zero angle of contact is assumed, then it is certain that the only isothermal equilibrium between a soil and a saturated water vapor would be complete saturation of the soil, as stated in the previous paper (6). Recent

experiments have been performed where the soils were kept in closed vessels containing water, and under practically isothermal conditions over a long period without apparent rise in the moisture content.

THEORETICAL INTERPRETATION OF THESE RESULTS

To determine the possibilities of such an experiment, it is illuminating to make a few calculations based upon well-established laws of physics. These calculations are of a technical nature but show how fast water vapor can be transported by diffusion under certain conditions. The vessel containing the free water and the soil samples must be isothermal, which means that at any time all parts of the vessel are at the same temperature and that the temperature of the vessel does not fluctuate. The need for this is obvious, since otherwise the results would be meaningless, as no equilibrium could be obtained. Under isothermal conditions there can be no convection currents in the air, and thus the vapor must be transferred from the water to the soil by diffusion and by no other method.

The thermal conductivity in C.G.S. units is the heat transferred across a centimeter cube per second when one face is 1°C. warmer than the other, and, if the fall in temperature for each centimeter through the body is known, from this the rate of heat transfer through any sized body can be calculated. Similarly the diffusion constant in C.G.S. units is the weight in grams of vapor diffused across a centimeter cube per second, if the concentration, or vapor density is 1 gm. per cc. greater on one face of the cube than on the other, and from this the diffusion rate for any sized space and any change in vapor density per centimeter can be calculated. It must be remembered that with heat the temperature drop per centimeter, or the gradient, can be many degrees per centimeter, whereas with water vapor the density at room temperatures is about 0.00001 gm. per cc., and the change per centimeter is a small part of this.

In order to calculate the difference in vapor density between the water and the soil, one must assume a certain size cavity to be filled. The water surface filling this cavity would have the same radius of curvature as the cavity. From the formula for the rise of liquids in capillary tubes, it is possible to calculate how far above a flat water surface this curved surface would have to be in order to be in mechanical equilibrium. Under isothermal conditions, mechanical equilibrium is established, then there must be vapor equilibrium. If this were not true, there would be a distillation of water, destroying the mechanical equilibrium and causing a cyclic flow of water, which is contrary to the second law of thermodynamics.

To carry out the calculation, first assume that the soil has cavities with a radius of curvature of 100μ, or 0.01 cm. In a capillary tube of this radius the water would rise to the height h in centimeters given by the formula $h = \frac{2T}{rg}$ Where T, the surface tension of water, is 72 dynes per cm., r is the radius in

centimeters, and g is the acceleration of gravity, 980 cm. per second; then $h = \frac{2 \times 72}{0.01 \times 980} = 14.7$ cm. This means that a water surface with a radius of curvature of 0.01 cm. would be in mechanical equilibrium with a free flat water surface 14.7 cm. lower. If it is in mechanical equilibrium, it must also be in vapor equilibrium, as explained in the foregoing. Then the difference in vapor pressure between the curved surface and the flat one would be the pressure due to the weight of a column of water vapor 14.7 cm. high. At 25°C. the vapor density of water is 0.000023 gm. per cc. Then, the difference in pressure at the two points is the weight of the column of vapor 14.7 cm. high, or $14.7 \times 0.000023 = 0.00034$ gm. per sq. cm.; or $\frac{0.00034}{13.6} = 0.000025$ cm. of mercury.

The vapor pressure of water at 25°C. is 2.4 cm. of mercury, and the vapor pressure of the curved surface is $\frac{0.000025}{2.4} = 0.0000104$ part less than the vapor pressure of the flat surface. The vapor density, would be less in the same proportion, or a difference of $0.000023 \times 0.0000104 = 0.000000024$ gm. per cc. in the density of the vapor above the flat and the curved surfaces of the water.

At this temperature, if the vapor is diffusing along a tube of 1 sq. cm. cross section, and the vapor density changes 1 gm. per cc. for each centimeter along the tube, then 0.25 gm. of water vapor will diffuse past a given point every second (0.25 being the diffusion constant for water vapor into air at 25°C. in C.G.S. units). Now, assuming the flat and curved surfaces to be placed 1 cm. apart and the area of the air path to be 1 sq. cm., the amount that would diffuse would be $0.25 \times 0.00000000024 \times 3600 \times 24 = 0.0000052$ gm. daily = 0.0019 gm. yearly. This means that it would take 530 years for 1 gm. to diffuse.

In practice, for the ordinary laboratory test, the area of the exposed soil and of the air path would probably be from 20 to 40 sq. cm., thus increasing proportionately to the total diffusion. However, since the soil would be about 10 cm. from the water, the gradient is decreased to one-tenth of that in the foregoing illustration and hence the net result would be a reduction in the required time of from one-half to one-fourth, meaning that it would still require from 100 to 200 years to distill 1 gm. of water, or 5 to 10 years to distill 0.05 gm., in other words, 5 to 10 years would be required to get a measurable amount of water distilled into the soil cans.

Another difficulty would be the necessity of saturating the air to a point within one part in a hundred thousand of complete saturation. To assure this one would have to be sure that the thermostat was constant to within 0.00016°C., and that all external radiation was excluded so that the system would be isothermal to within that figure, or there would be no systematic transfer in a given direction.

In order to prove that an equilibrium state drier than complete saturation exists, one must recognize and take account of the following conditions: In

order to fill the air pockets in the soil one must be prepared to allow the experiment to run over a period of many years, that is, 100 years for each gram of water transferred, after the pores are 0.01 cm. in radius. The temperature control must be accurate and no external radiation can be allowed in the chamber, since after the pores are 0.01 cm. in radius the temperature must be controlled to within 0.00016°C.

The time can be shortened and the variations of temperature can be allowed to be greater if the following changes are made: (*a*) stirring the air in the chamber, the transfer being made mechanically instead of being left to the slow process of diffusion (6, 8); (*b*) by using fine soils or soil separates, one can reduce the size of the largest pores and thus increase the vapor pressure gradient as well as the limit of temperature variation allowable.

In order to realize this equilibrium, however, working under the most advantageous conditions, the experiment must be accurately controlled and run over almost prohibitive periods for the continuous operation of fine constant temperature apparatus.

APPLICATIONS

In spite of the fact that the approach to equilibrium with free water is very slow, the assumption that it is reached just because the changes are too slow to be measured is not justified. There are definite properties peculiar to an equilibrium condition, and the assumption of equilibrium where it does not exist leads to inconsistent results. The end point reached under such conditions depends upon the apparatus and the experimental procedure, whereas an equilibrium is independent of the apparatus and of the method used to reach it. This is assuming that in every case equilibrium was reached. An example of this was pointed out in a previous paper (6), where two sets of workers, trying to determine the so-called hygroscopic coefficient with different apparatus, reported opposite temperature effects. One reported an increase with increasing temperature and the other a decrease. Coupled with the fact that equilibrium had not been reached, these results were shown to be the natural outcome of the experimental methods used. It was also shown that one of the inherent characteristics of the isothermal equilibrium between soil and free water is its independence of the temperature.

This slow rate of water transfer begins while the soil is too dry to sustain plant life and continues to a complete saturation. In coarse soils this means that most of the moisture content of a saturated soil must be added after the vapor pressure is very near that of pure water.

In this connection it might be of interest to note how the extremely small values of the rates of diffusion of water vapor through air, as shown by the foregoing calculation, indicate how little moisture would be lost from a soil by diffusion from the lower layers. The vapor pressure gradients would be greater than those in the calculation mentioned, but the soil reduces the

effective area available for the transfer of vapor, thus tending to counteract this increase.

The amount of vapor lost by this mode of transfer, however, would be small compared with other modes of loss. The loss due to the breathing, or the movement of air into and out, of the soil resulting from barometric and temperature variations, would probably be greater than that due to pure diffusion. In case a deep mulch is prepared, the capillary transfer would be reduced; the diffusion out of the soil would be reduced because of the increased distance that the vapor must diffuse; and the loss through breathing would be diminished, since greater fluctuations of temperature and pressure would be required to move the air from the damp soil below to the free air above.

In connection with the experiment on the capillary rise of water in the soils, some tests were made as to the relative rates of the rise of water from the bottom of a tube and the seeping of water down from the top. Some previous experimenters having reported that the seeping down was a slower process, especially when the water was placed on soil in bottles or closed-bottomed tubes, tests were made with the bottom of the tube open and closed. With the Greenville loam, when the bottom of the tube was left open the movement down from the top went unhampered; but when closed, the water soaked down a centimeter or two, then the wet and dry parts of the column of soil separated and practically stopped all flow. By alternately opening and closing the bottom of the tube, the following action was evident: With the tube closed the water soaked down the tube, sealing it off and prohibiting the escape of air. As it went farther down, the air was compressed, and finally the wet soil, acting as a plug or piston, was forced upward, breaking the soil and thus the liquid connection to the soil below. When the bottom of the tube was opened, the wet plug slid down, making contact again. Plate 1 shows the results of such a test. Similar results are to be expected where there are no provisions for the escape of the air from the soil into which the water is moving. Thus it is evident that this slower flow downward is not a result of a finite angle of contact between water and soil particles, as has been suggested.

CONCLUSIONS

The angle of contact between clean glass and water is zero or very small.

The angle of contact between water and clean faces of many of the minerals found in soils is zero or small.

Foreign substances, especially fats and fatty acids, cause large angles of contact.

Oleic acid films on soil particles change the capillary characteristics of the soil so markedly as to indicate that there is little of this class of substance in the soil used.

Experiments in an attempt to show that there is an equilibrium between a soil and a saturated water vapor, drier than complete saturation of the soil,

must be run with no variation of temperature in the system of more than 0.00016°C. and must extend over an uninterrupted period of more than 100 years to absorb 1 gm. of water after the pores are 0.01 cm. in radius.

At the so-called hydroscopic coefficient, even though the water vapor movement is extremely slow, when measured by moisture content, the soil is far from equilibrium. Serious theoretical mistakes can be made and experimental difficulties caused by assuming equilibrium when the moisture transfer is too slow to be detected by ordinary methods.

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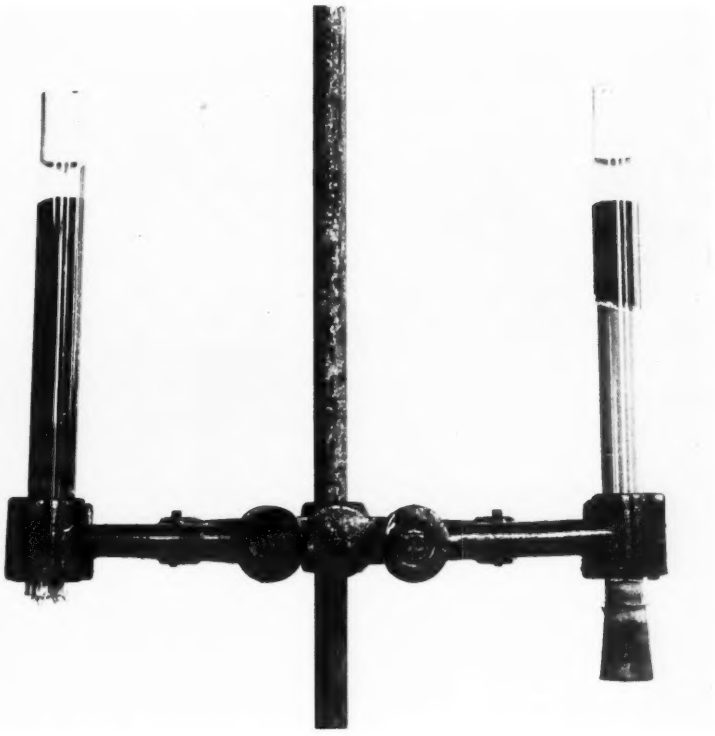
PLATE 1

EFFECT OF WATER SEEPING DOWN INTO A CLOSED VESSEL

The tube at the left was closed at the bottom with a porous plug, that at the right with a rubber stopper. Water was added to both at the top. The soil at the left was completely saturated. At the right the movement of the water into the soil trapped the air, and finally the pressure was great enough to force the wet soil, as a body, upward far enough to separate the soil column and practically stop the flow of water.



DETERMINING SOIL ORGANIC MATTER BY MEANS OF HYDROGEN PEROXIDE AND CHROMIC ACID

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Recently G. W. Robinson and J. O. Jones (9) proposed a method for determining the degree of humification of soil organic matter by oxidizing the humified part with a dilute solution of hydrogen peroxide. According to W. O. Robinson (10) the total soil organic matter can be oxidized by means of concentrated hydrogen peroxide; he suggested the use of this as a quantitative method, thereby proving that the conclusions reached by the method proposed by G. W. Robinson and J. O. Jones are erroneous, for the hydrogen peroxide not only oxidizes the humified substances but also decomposes completely all other forms of organic matter.

From the investigation of G. W. Robinson, we may infer that a method may be discovered by which the oxidation may affect only the humified part of soil organic matter. An assumption is thereby made that through the action of hydrogen peroxide, the artificial humification of undecomposed residues is first obtained, and only afterwards does complete oxidation of the whole soil organic matter result. This may well corresopnd to the assumption that there is a sufficiently resistant or humified part of organic matter, which prevents the method of G. W. Robinson and J. O. Jones from accomplishing its purpose.

The method of W. O. Robinson is much more convenient for the determination of the total organic matter; however, although the fundamental idea is fairly simple, this method possesses certain defects, the greatest of which is the undue length of time required. Thus, it is desirable to invent a quicker and simpler method.

The most renowned and classical methods, those of Liebig-Gustavson (4) and Knopp-Sabanin (12), namely, the indirect determination of soil organic matter by the dry or wet combustion method, also have important defects, especially their slowness.

The method suggested and described by Schollenberger (14) for the approximate determination of soil organic matter is highly interesting since he endeavors to solve this problem by applying, for the purpose of oxidizing the organic matter, a standard solution of chromic acid and determining the amount of chromic acid thereby reduced.

It seems quite obvious that the method proposed by Schollenberger cannot assume a precise definition of the organic fraction, as it is impossible always to heat solutions of chromic acid to exactly 175°C. in a test tube over a low flame, for discordant results may be obtained in parallel and even in blank determinations. Nevertheless, the idea of Schollenberger's method must be acknowledged as the most convenient in all respects; it is very desirable to elaborate and enlarge the method for general utilization, modifying it so as to secure more constant and exact determinations.

In Russia, Istcherecoff (5, 6) has suggested a method for determining the soil organic matter by oxidizing it with a standard solution of potassium permanganate, but this method is open to considerable criticism (1, 2, 3, 8, 11, 15, 19).

Istcherecoff's method does not lay claim to being a rapid determination, for at least an hour is required to heat the solution with soil, which seems rather too long; an exact definition of the organic matter thereby oxidized is impossible because of the side reaction of reduction of a standard solution of potassium permanganate in the process of heating.

TABLE 1

The oxidation of sugar by means of chromic acid

Weight.....*gm.*	0.0106	0.0118	0.0102	0.0084	0.0116
Reduction of chromic acid equal to Fe..*cc.*	7.5	8.3	7.1	5.9	8.2
Carbon found.....*gm.*	0.004466	0.004953	0.004228	0.003513	0.004885
Theoretical quantity of carbon.....*gm.*	0.004463	0.004960	0.004229	0.003532	0.004884
Difference.....	0.000003	0.000007	0.000001	0.000019	0.000001

The method of Schollenberger, using the chromic acid standard solution for the oxidation of organic matter, is, of course, more convenient, where improvements of only certain processes are necessary.

EXPERIMENTAL

In accepting the method of Schollenberger, one must first become familiar with the reaction between the chromic acid and the ferrous ammonium sulfate solutions. Though this reaction is simple in its manner, for precise and accurate determinations one must study the tint between the diphenylamin and chromic acid and also a subsequent modification of its hue at the titrating process to the proper end point. It is also necessary to determine by heating the standard solution of chromic acid to 175°C., whether it undergoes any changes.

As a result of experimental investigation into the method of Schollenberger, the following modifications have been included:

1. The weight of soil was reduced to 0.2–0.15 gm. (instead of 0.5 gm.) which does not affect its precision.

2. The standard solution of chromic acid is prepared by dissolving 16 gm. of CrO_3 in a liter of concentrated sulfuric acid. This compound is heated to 165°C. for one-half hour, and is then ready for titration. Because of its careful preparation, the solution leaves no precipitate, and the titer becomes more stable.

3. The oxidation of soil organic matter by 10 cc. of chromic acid solution is brought about in a test tube which is heated for 10 minutes at a temperature of 165°C. in a sulfuric acid bath. Under these circumstances a blank shows no alteration in its titer, therefore a control is less needed because of the constant temperature (165°C.) of the liquid bath.

4. For the complete oxidation, 10 minutes is sufficient. After the test tube is cooled, its contents are washed into a beaker, diluted with water to 200 cc., and titrated against the ferrous ammonium sulfate solution in the presence of 1 cc. of diphenylamin solution, until the deep blue color changes to a muddy green.

5. The results may be expressed in the percentage of carbon by weight.

To verify the accuracy of this modified method of Schollenberger, we used the following pure substances to determine their carbon content: glucose,

TABLE 2

The oxidation of carbon in the soil by means of chromic acid

Soil weight.....*gm.*	0.1448	0.0406	0.1256	0.1180	0.1436
Reduction of chromic acid equal to Fe..*cc.*	8.6	2.4	7.4	6.9	8.1
Carbon found.....*gm.*	0.005122	0.001429	0.004407	0.004109	0.004824
Carbon.....*per cent*	3.54	3.52	3.51	3.48	3.36
Average.....*per cent*	3.48	3.48	3.48	3.48	3.48
Difference.....*per cent*	0.06	0.04	0.03	0.00	0.12

TABLE 3

The determination of soil carbon by the Knopp-Sabanin method

Soil weight.....*gm.*	0.2988	0.2718	1.0860	1.3334	1.0756	1.2512	0.2480
Carbon found.....*gm.*	0.0096	0.0106	0.0375	0.0414	0.0368	0.0420	0.0096
Carbon.....*per cent*	3.21	3.90	3.45	3.11	3.42	3.36	3.88
Average.....*per cent*	3.48	3.48	3.48	3.48	3.48	3.48	3.48

starch, crude fiber, sucrose, other sugars, and resorcin. A summary of the results is given in table 1.

One cubic centimeter of ferrous ammonium sulfate solution was equivalent for the titration of 0.0005955 gm., or roughly, 0.0006 gm. of carbon. Thus it may be seen that by overtitrating to 0.1 cc., the error would be 0.00006 gm. of carbon for one full weight, or a smaller percentage than that usually allowed for experimental error.

The weight of 0.2 gm. is enough for the exact determination of carbon contents, and the possible error will average 0.03 per cent.

From the figures in table 1, the sensitiveness of the operation is evident.

By adopting the same method for the determination of soil carbon we obtain the results shown in table 2. A comparison of these results can be

made with those obtained by the method of Knopp-Sabanin, the same sample of soil being treated, with the results shown in table 3. It is evident that the modified volumometric method of Schollenberger is superior to the method of Knopp-Sabanin.

By the modified method of Schollenberger, previously described, the results are obtained in an indirect way. Undoubtedly the entire amount of carbon in the soil organic matter is oxidized completely by chromic acid into carbon dioxide:

$$3C + 4H_2CrO_4 + 6H_2SO_4 \rightarrow 3CO_2 + 2Cr_2(SO_4)_3 + 10H_2O.$$

If we allow the liberated carbon dioxide to be absorbed by a standard solution of barium hydroxide, in a specially constructed apparatus, by titrating with standard sulfuric or standard hydrochloric acid solution we may in a direct way determine the quantity of carbon dioxide absorbed by the barium hydroxide. This process is very simple and accurate but requires 40 minutes to complete one operation.

A NEW OXIDIZING METHOD

While the method of Schollenberger was being investigated and its properties studied, a new method was found of oxidizing the soil organic carbon with hydrogen peroxide and chromic acid solutions. Since the complete oxidation of soil organic matter by means of these solutions took place in a series of simultaneous reactions a process was evolved which rapidly oxidizes soil organic matter without the application of exterior heat.

Solutions required

1. Hydrogen peroxide solution (0.3 per cent)—to each liter of solution 25 cc. of concentrated sulfuric acid is added.
2. Chromic acid solution—16 gm. of CrO_3 to a liter of concentrated sulfuric acid (the solution is prepared by heating to 165°C.).
3. Ferrous ammonium sulfate solution $[Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O]$—79.8 gm. dissolved in each liter of solvent made up of 40 cc. of sulfuric acid dissolved in 1 liter of water.
4. Diphenylamin—0.5 gm. to 100 cc. of concentrated sulfuric acid and 20 cc. of water.

Procedure

From 0.2 to 0.15 gm. of air-dried soil, finely crushed and carefully run through a 0.25-mm. sieve is put into an oval-bottomed, long-necked, 100-cc. vessel. Over this is poured a solution of 10 or 15 cc. of hydrogen peroxide; then 10 or 15 cc. of chromic acid solution is added (on the sides of the vessel); the compound is shaken by hand for one minute with vigorous circular movements. Considerable heat is generated and a complete oxidation of soil organic matter takes place.

The contents of the vessel are washed into a beaker, diluted with water to 200 cc., and the residue of chromic acid is titrated against ferrous solution in the presence of diphenylamin. A blank is thus obtained, and the difference between the amount of ferrous solution used for the titration of the blank and that for the soil sample is a measure of the amount of carbon in the soil organic matter. To find the logarithm of the carbon content in a given weight of soil, we must add to the logarithm of the "carbon figure" (i.e. of the quantity of carbon which corresponds to 1 cc. of ferrous solution) a logarithm of the difference in cubic centimeters of ferrous solution. The amount of carbon determined may be expressed as a percentage of the soil weight. Only 10 minutes is required for the entire determination.

Results

In order to prove the applicability of this oxidizing method to the quantitative determination of carbon in the soil organic matter, a series of experiments was run on pure organic substances, such as starch, sugar, and glucose.

TABLE 4

Comparison of the author's oxidizing method with that of Liebig-Gustavson

	STANDARD NO. 4			STANDARD NO. 14		STANDARD NO. 10		STANDARD NO. 15	
Soil weight.....*gm.*	0.1202	0.1132	0.1206	0.1522	0.1226	0.1134	0.1122	0.1476	0.1074
Carbon found by oxidizing method...*per cent*	3.123	3.165	3.066	2.94	2.98	3.41	3.44	3.98	4.02
Average.....*per cent*	3.114			2.96		3.43		4.00	
Carbon found by Liebig-Gustavson method *per cent*	3.108			3.01		3.44		3.93	
Difference.....	0.006			0.05		0.01		0.07	

In all oxidations of these pure organic matters, the difference between the theoretical quantity of carbon in the weight employed and the practical content revealed, was found to vary from 0.005 mgm. to 0.001 mgm. for a substantial weight of 200 mgm. Thus the possible error of over-titration of 0.1 cc. may be equal to 0.02 per cent on 200 mgm., which is a small error as compared with the usual error in macrotitrometrical determinations.

Since a complete decomposition of the carbon into carbon dioxide was assured, this method of oxidation was applied to the quantitative determination of carbon in the soil.

The results obtained by the application of this method, compared with those obtained by the method of Liebig-Gustavson for several types of the soils are shown in table 4.

The close agreement between the results of the Liebig-Gustavson method and of the newly adopted one, which are confirmed by our manifold analytical

data, gives us reason to expect good results in applying this method to a quantitative determination of carbon in the soil.

The preëminent advantages of this method are its simplicity, its rapidity, and its adaptability to numerous determinations.

For the perfecting of this method, certain improvements and determinations of the essential point of reaction of hydrogen peroxide and chromic acid solution on soil organic matter are necessary.

The reaction between chromic acid and hydrogen peroxide solutions proved that when the hydrogen peroxide is completely decomposed, the chromic acid is then reduced to some equivalent quantity. The equivalents of chromic acid and hydrogen peroxide for this reaction were found to be in the proportion of 2 gram-molecules of chromic acid to 3.03 gram-molecules of hydrogen peroxide destroyed. Hence we have the following equation:

$$2H_2CrO_4 + 3H_2O_2 + 3H_2SO_4 = Cr_2(SO_4)_3 + 8H_2O + 6O^{m}.$$

Because of the combined action of these two solutions upon the soil organic matter, a constant reaction between them takes place, but the essential point requires subsequent investigation.

In spite of the results obtained and of the continuing investigations of this chemical process, the method may be transformed from an indirect to a direct one, like the methods of Liebig-Gustavson or Knopp-Sabanin, by determining the quantity of carbon by means of carbon dioxide. For this purpose we need only the record of the carbon dioxide obtained.

It is indubitably affirmed that by the application of this oxidation reaction the carbon of soil organic matter oxidizes wholly and completely into carbon dioxide. It is only necessary to construct a special set for a volumometrical gas analyses to determine the smallest amounts of carbon dioxide. A more precise determination may ensue and the definite results may appear more probable.

The work on this method is to be continued.

SUMMARY

This work is especially devoted to the investigation of the rapid methods for determining organic carbon in the soil. A rapid approximate method for determining soil organic matter, treated by Schollenberger, was particularly revised, and certain alterations were introduced into it. Besides the revision and alteration of the method of Schollenberger, another method of complete oxidation of soil organic matter by means of hydrogen peroxide and chromic acid solutions, without the use of outside heat, was developed and applied to the quantitative determination of carbon in the soils.

The results obtained by this new method show a close agreement with those obtained by the method of Liebig-Gustavson.

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CHILEAN NITRATE OF SODA NITROGEN RESEARCH AWARD

About two years ago the Chilean Nitrate of Soda Educational Bureau of New York made available an annual appropriation of $5,000 to be distributed in the form of one or more prizes for outstanding research, in this country and Canada, on nitrogen in its relation to soil processes and plant growth. The above sum has been placed in the hands of the American Society of Agronomy, the award being administered by a special committee of the society.

The first awards were made in 1928. The committee held then that it was advisable to select older investigators whose previous work in advancing knowledge of nitrogen in relation to plant growth had been beyond question. Prof. J. G. Lipman, director of the New Jersey Agricultural Experiment Station; Prof. T. L. Lyon, chief of the soil department, Cornell University; Prof. E. B. Fred, division of agricultural bacteriology, University of Wisconsin; and Prof. F. T. Shutt, Dominion chemist, Ottawa, Canada, were those selected. In connection with the announcement of the selections for 1928, the committee suggested that subsequently it would be appropriate to consider and perhaps even given preference to those younger investigators who have made recent contributions to the subject.

The second award, announced at the 1929 meeting of the society, was divided among three investigators; namely, Prof. C. A. Mooers, director of the Tennessee Agricultural Experiment Station; Prof. P. L. Gainey, soil bacteriologist of the Kansas Agricultural Experiment Station; and Prof. S. A. Waksman, microbiologist of the New Jersey Agricultural Experiment Station.

In order to make clear the nature of the investigations that will be considered for the award in 1930, the committee feels that it is desirable to publish a brief statement at this time.

Investigations will be considered which deal with the physical, chemical, or microbiological transformation of both organic or inorganic nitrogen in the soil, the absorption and utilization of nitrogen by plants, and nitrogen fertilizer in any of its aspects. The committee will give particular attention to those contributions which have been published within the past year or two. Investigations of longer standing will also be considered, provided the authors are still actively engaged in the work.

Investigations dealing with any phase of nitrogen in relation to soils and crops may be called to the attention of the committee either by an author himself or by any one else. The award, which may be made either to one or more investigators, will be recommended to the society, according to the judgment of the committee.

The committee takes this opportunity to solicit nominations of candidates for the 1930 award. The nominations should be made in writing and may be addressed to any member of the committee. Although it may be difficult to select the "most" outstanding contribution to such a complex subject as nitrogen in its relation to soils and plants, the committee hopes at least to be able to select one or more investigators who have made a notable contribution to the scientific understanding of the rôle of nitrogen in soils and plants. It is expected that the award will be used in such a way as to lead to still higher scientific activity.

The award is open to investigators irrespective of their connection with the American Society of Agronomy. The investigation may have been made at a university, state experiment station, government institution, or privately.

Chilean Nitrate of Soda Nitrogen Research Award Committee.

R. W. THATCHER
C. B. WILLIAMS
W. P. KELLEY
R. I. THROCKMORTON
R. BRADFIELD
S. A. WAKSMAN, *Chairman.*

SECOND INTERNATIONAL SOIL SCIENCE CONGRESS PLANS

In a recent issue of SOIL SCIENCE[1] general plans were announced for the Second International Congress of Soil Science, to be held in Leningrad and Moscow, U. S. S. R., beginning July 20, 1930. Tentative plans were given for the second, third, fifth, and sixth commissions. Programs for the first and fourth commissions and more detailed programs than those already given for the second and fourth commissions are now also available and include the following topics:

FIRST COMMISSION

1. Preparation of the Soil Sample for Mechanical Analysis.
2. Definitive Decision in the Question of Fractioning Soil Kernels.
3. Report on the Single Values.
4. Determination of the Chief Physical Properties of Soils in Regard to the Natural Structure.
   a. Specific gravity; real and apparent.
   b. Porosity.
   c. Water-holding capacity.
   d. Air-holding capacity.
   e. Permeability.
5. Normal Apparatus for the Mechanical Analysis of Soil.

Members are requested to limit their papers to the aforementioned questions in so far as possible.

SECOND COMMISSION

1. Hydrochloric acid extract.
2. Soil acidity and adsorption.
3. Determination of plant nutrients by laboratory methods.
4. Organic matter of soil.
5. Other subjects.

Alkali Subcommission

1. World literature of alkali and salty soils.
2. Genesis of alkali soils.
3. Alkali soil survey and phenology.
4. Analytical methods of alkali soil investigation.
5. Reclamation and utilization of alkali soils.
6. Microbiology and organic matter of alkali soils.
7. Other subjects.

The titles of the papers, to be presented before the second commission, received to January 21 are as follows:

Dr. F. L. Smolik: The uniformity of the pH values in forest soils.

Sch. R. Zinzadze: Ein neues Reagens zur Kolorimetrischen Bestimmung der Phosphor- und Arsensäure in Bodenauszügen.

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Sch. R. Zinzadze: Studien über die Löslichkeit von einigen im Boden vorkommenden Phosphaten.

Sch. R. Zinzadze: Absorption von P_2O_5 durch Bodenkolloide sowie dessen Einfluss auf die Löslichkeit von Phosphaten.

E. Pfeil: Über den Einfluss der Zustandsform des Mangans und Eisens auf die Katalytische Kraft gesunder und säurekranker Böden.

Yoshisaburo Kida: On the solubility of iron and aluminum phosphates as influenced by alkalies.

Alkali Subcommission

D. Vilensky: Brief history and summary of investigations of alkaline and saline soils in U. S. S. R.

D. Vilensky: The process of regradation of saline and its place in the circle of evolution of salty soils.

FOURTH COMMISSION

1. The Determination of the Manurial Requirements of the Soil by Means of Plant Physiology.
   a. Field experiments.
   b. Mitscherlich's pot experiments.
   c. Wiessmann's pot experiments.
   e. Further physiological methods.
2. The Determination of the Lime Requirements of the Soil by Plant Physiological Methods.
3. Soil Reaction and Plant Productivity. Consideration of the Sensitiveness of the Various Domestic Plants to Reaction.
4. Reaction of the Soil and Absorption of Nutrition by Plants.
5. Reaction of the Soil and Plant Parasites.
6. The Influence of the Cultivation of the Soil on the Plant Yield.

FIFTH COMMISSION

1. The Genesis of Soil.
   a. The influence of parent rock on soil formation.
   b. Soil minerals.
   c. Permanently frozen soil layers and their influence on soil formation.
   d. Genesis of forest soils or forest vegetation as a factor of soil formation.
   e. Genesis and types of mountain soils.
   f. Laterites and red soils.
   g. Weathering and soil formation processes in deserts.
   h. The action of salification and desalification.
   i. Characteristics of separate types of soil formation.
   j. Soil types of U. S. S. R.
2. Classification and Nomenclature of Soils.
   a. The main principles of soil classification.
   b. General soil classification of all countries.
   c. Soil horizons and their designation.
   d. Normal scale of soil colors.
   e. The subdivision of soils for practical purposes.
3. Geography and Cartography of Soils.
   a. Reports on soil maps: Asia, Europe, America, Africa, Australia, and the territory of the U. S. S. R.
   b. Regional geography of soils.
   c. The mapping of soils in detail.